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LOW-PRESSURE PERFORMANCE OF A TUBULAR COMBUSTOR WITH GASEOUS HYDROGEN

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RESEARCH MEMORANDUM

LOW-PRESSURE PERFORMANCE OF A TUBULAR COMBUSTOR WITH GASEOUS HYDROGEN

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SUMMARY

An investigation was conducted to determine the combustion performance characteristics of gaseous hydrogen fuel in a single tubular turbojet combustor. The combustor was operated over a range of inlet-air pressures from 3.3 to 14.3 inches of mercury absolute. Reference velocities as high as 174 feet per second were investigated to pressures as low as 8.0 inches of mercury absolute; reference velocities at lower pressures were limited to lower values by the test facility. Limited comparison tests were conducted with gaseous propane fuel.

Hydrogen fuel burned over very broad ranges of temperature rise at all pressure conditions investigated. No combustion instability or flame blow-out was observed. Combustion efficiencies in excess of 90 percent were maintained to pressures as low as 8.0 inches of mercury absolute with velocities as high as 174 feet per second. At pressures below 8.0 inches of mercury absolute, marked decreases in efficiency were observed.

Propane operated over only a very limited range of temperature rise; combustion efficiencies were lower than those obtained with hydrogen and were adversely affected by increases in reference velocity and decreases in inlet-air pressure. The superior performance of the hydrogen is attributed to its higher flame speed and wider flammability range. The fact that 100-percent combustion efficiency was not obtained over a broad range of operating conditions is attributed to inadequate mixing of the fuel and air in the primary zone of the combustor used for the tests.

INTRODUCTION

A research program is being conducted at the NACA Lewis laboratory to improve combustion efficiency and combustion stability limits of turbojet combustors. The use of a special fuel to provide improved performance at very low operating pressures is described in this report.

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The limits and efficiency of combustion in the turbojet are seriously reduced at low operating pressures encountered in low-speed, high-altitude flight. Current combustors in engines with pressure ratios of 5 can be operated at subsonic flight conditions to altitudes of about 45,000 feet while maintaining efficiencies over 90 percent (ref. 1). Experimental combustors have been developed (ref. 2) that maintain this same level of performance to altitudes of 70,000 feet. The pressures encountered in subsonic flight at 70,000 feet are of the order of 4 to 5 pounds per square inch absolute for a compressor pressure ratio of 5. 3614
Some applications for combustors may require operation at pressures well below this range. For example, a very high-altitude (100,000 ft) low-speed aircraft might require combustion at pressures as low as 1 to 3 pounds per square inch absolute; very low pressures would also be encountered in a combustor supplied with air from a ducted fan, or in an afterburner.

A promising alternative to further design improvements for attaining the required performance is the use of a special, highly reactive fuel. Depending upon airframe requirements, logistics, and other factors, this special fuel may constitute (1) the main fuel supply to the engine, (2) a pilot fuel to aid combustion of the main fuel, or (3) an alternate fuel supply for use only during operation at the very severe conditions.

To evaluate the performance characteristics of one possible "special fuel," low-pressure combustion tests were conducted with a tubular turbojet combustor supplied with gaseous hydrogen fuel. The tests were conducted at pressures from about 3 to 14 inches of mercury absolute, and reference air velocities from 70 to 170 feet per second. The results are analyzed to indicate the low-pressure combustion performance characteristics obtained with hydrogen, and the effect of fuel-injector size and design on the performance of this fuel. The data are compared with limited data obtained with a gaseous hydrocarbon fuel, propane, at some of the conditions investigated.

APPARATUS

Combustor Installation and Instrumentation

The installation of the single J33 combustor is shown schematically in figure 1. Air having a dewpoint of either -20° or -70° F was supplied to the combustor from the laboratory supply system; the hot exhaust gases from the combustor were cooled and fed to the laboratory exhaust system. The air flow to the combustor was measured with a square-edged orifice plate installed according to A.S.M.E. specifications and located upstream of the flow-regulating valves. The combustor-inlet air temperature was regulated by means of electric heaters.

A diagrammatic cross section of the combustor installation showing the position of instrumentation planes and the location of temperature- and pressure-measuring instruments in these planes is presented in figure 2. Thermocouples and total-pressure tubes were located at centers of equal areas. Construction details of the instrumentation probes are shown in figure 3. The combustor-inlet and -outlet temperatures were indicated on automatic balancing potentiometers. The inlet and outlet total-pressure data were obtained with manometers connected to 12 manifolded probes at stations A-A and D-D (fig. 2).

Fuel Supply System

A schematic diagram of the system used to supply gaseous fuel to the single combustor is presented in figure 4. Hydrogen was stored in 38 cylinders, manifolded together, at a pressure of 2600 pounds per square inch. Each cylinder contained about 2780 cubic feet (at standard atmospheric conditions) of hydrogen. The hydrogen was drawn from one or more of the cylinders through a reducing valve, filter, rotameter, throttle valve, check valve, and into the combustor. A relief valve and a pressure switch, vented to the atmosphere, were installed to protect the system against excessive pressures. Analysis indicated the hydrogen to be at least 99 mole percent pure. Gaseous propane fuel was supplied from approximately 800-cubic-foot cylinders (at standard atmospheric conditions) at 120 pounds per square inch through the same system that was used for the hydrogen. The purity of the propane was estimated by the supplier to be at least 96 mole percent.

Fuel-flow rates to the combustor were measured by rotameters. The rotameters were calibrated with air at temperature and pressure conditions that provided fluid densities approximately the same as those of the test fuels at the test conditions. Appropriate density corrections were then applied to the rotameter measurements.

Fuel Injectors

A number of fuel injectors were used in this investigation to obtain a variation in injection characteristics. Construction details of these injectors are shown in figure 5. Injectors A, B, and C were commercial hollow-cone swirl-type nozzles modified by removing the swirl parts and adding six equally spaced holes positioned 45° from the axis of the nozzle. Injector D was a similar commercial nozzle modified by removing the swirl parts, enlarging the central orifice, and facing the tip of the injector to form a sharp-edged orifice. Injector E was similar to the modified "axial tube" injector used for gaseous fuel injection in the investigation reported in reference 3. Injector E was designed to introduce the fuel at a more gradual rate to avoid over-rich fuel-air mixtures in the upstream primary-combustion zone. The orifices in injector E were arranged to provide an axial distribution of fuel-orifice area approximately the same as the axial distribution of air-entry area contained in the perforations in the walls of the combustor liner.

The flow-rate - pressure-drop characteristics of these fuel injectors are presented in figure 6. Injectors B, D, and E have similar pressure-drop characteristics.

PROCEDURE

The combustion performance of gaseous hydrogen fuel was determined at the following combustor operating conditions:

Inlet-air total pressure, in. Hg abs	Air-flow rate, lb/sec	Reference velocity,[a] ft/sec	
		Inlet-air temperature, °F	
		40	200
14.3	0.80 1.00 1.30	80 100 131	105 132 173
8.0	0.56 .73	100 132	133 174
6.2	0.50	115	153
3.3	0.15	65	83

[a]Based on combustor maximum cross-sectional area of 0.267 sq ft.

The reference velocities are average values; some variation in air-flow rate was tolerated at the lower pressure conditions because of limitations in the flow control system used. For the air velocities and combustor temperature-rise conditions of interest, a pressure of 3.3 inches of mercury absolute was the minimum pressure that could be maintained in the facility.

At each of these combustor-inlet conditions, hydrogen performance data were recorded over a wide range of fuel-air ratios; this range was limited by (1) fuel-flow metering equipment, (2) fuel supply, or (3) excessive combustor-outlet temperatures. Several minutes were allowed for combustion to stabilize at each condition before the performance data were recorded. The spark plug used for ignition was de-energized during operation.

For comparison purposes, combustion tests were conducted with gaseous propane fuel at the following inlet-air conditions:

Inlet-air total pressure, in. Hg abs	Air-flow rate, lb/sec	Reference velocity, ft/sec	
		Inlet-air temperature, °F	
		40	200
14.3	0.80	80	105
	1.00	--	132
	1.30	--	173
8.0	0.56	--	133
	.75	--	178

CALCULATIONS

Combustion efficiency was calculated as

$$\frac{\text{Actual enthalpy rise across combustor per lb of air}}{\text{(Fuel-air ratio)(Heating value of fuel)}}$$

For test data obtained with hydrogen, the enthalpies at the combustor inlet and outlet were determined from the charts presented in figure 7. These charts were constructed from data of reference 4, assuming the following reaction to occur:

$$H_2 + \frac{O_2 + 3.78N_2}{2} + \text{excess air} \rightarrow H_2O + 1.89N_2 + \text{excess air}$$

The enthalpy of the inlet hydrogen-air mixture was based on the air temperature at station B-B (fig. 2); the enthalpy of the exhaust gases, on the arithmetical average indication of the 16 chromel-alumel thermocouples at station C-C (fig. 2). The enthalpy of the exhaust gas was not corrected for variations in composition due to inefficient combustion; that is, only water, nitrogen, and oxygen were assumed to be present in the exhaust gases. A heating value for pure hydrogen of 51,571 Btu per pound (literature value) was used.

Combustion efficiencies obtained with propane were calculated by the method described in reference 5, using the same inlet and outlet

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temperature measuring stations. A heating value for the propane fuel of 19,930 Btu per pound (literature value) was used. The small amount of impurities present in this fuel would not affect its heating value, since the impurities have heating values close to that of propane.

RESULTS

The combustion performance data obtained with hydrogen fuel in the single J33 combustor are presented in table I. The combustion efficien- 3614
cies are plotted as a function of temperature rise in figure 8. The check data shown in this figure (tailed symbols) indicate a maximum deviation of almost 10 percent in combustion efficiency, the larger deviations occurring at the lower operating pressures. This indicated reproducibility of data is poorer than that normally expected in turbojet combustion tests. The factors that are believed to have contributed to the poor reproducibility include: (1) rotameters have been observed frequently to given inconsistent gaseous fluid flow measurements, (2) limited hydrogen supply required more rapid recording of the data, with less time being allowed for combustion to reach equilibrium conditions, and (3) small variations in inlet pressures and temperatures occurred during data recording operations. Fuel-flow measurements were subject to particularly large errors at the very low flow rates required for low-pressure, low-temperature-rise operation. Two rotameters were used to obtain the data in different ranges of fuel-flow rate, and these rotameters did not, in all cases, provide equivalent results. Inlet-air conditions were particularly subject to variations at the very low pressure, where the maximum capacity of the exhaust system was being utilized.

The performance data presented in figure 8 show that, in practically all cases, combustion efficiency decreased with an increase in temperature rise. Combustion efficiencies near 100 percent were attained at the highest pressure condition, 14.3 inches of mercury absolute (figs. 8(a) to (f)). Large decreases in efficiency occurred only when the inlet pressure was reduced below 6.2 inches of mercury absolute. Considering the reproducibility of the data, the variations in nozzle design investigated had very little effect on combustion efficiency. In a number of cases single curves are used to represent the data obtained with two different nozzles. The most significant effects of fuel-injection characteristics were observed at very low temperature-rise conditions.

The data obtained with propane fuel are presented in table II; the variation in combustion efficiency with temperature rise, for each of the operating conditions investigated, is shown in figure 9. Combustion efficiency generally decreased both at low and at high values of temperature rise. Maximum values of temperature rise and flame blow-out were observed at most of the operating conditions investigated. Efficiencies near 100 percent were attained only at high-pressure, low-velocity conditions; they decreased rapidly with a decrease in pressure and with an increase in reference velocity.

Included in figure 9 for comparison are faired curves representing the performance of hydrogen under similar operating conditions.

DISCUSSION

Stability Limits

The data that have been presented show that gaseous hydrogen will burn in an essentially unmodified turbojet combustor to pressures as low as 3.3 inches of mercury with velocities at that pressure of the order of 65 to 80 feet per second. Limitations in the test facility prevented operation of the combustor at more severe conditions. From the observed stability of combustion, however, it is considered probable that satisfactory operation could have been maintained at even more severe conditions. At higher pressures, where larger flow capacities were available, combustion was maintained to velocities of 153 feet per second at 6.2 inches of mercury absolute, and 174 feet per second at 8.0 inches of mercury absolute. Combustion could also be maintained over a very broad range of fuel-air ratio (or temperature rise). Fuel-air ratios as low as 0.0002 were investigated, with no flame blow-out being observed. The highest fuel-air ratios investigated were always limited by facilities or by instrumentation and never by flame blow-out.

The poor stability characteristics observed with gaseous propane at high fuel-air ratios (fig. 9) are to be expected, since this combustor was designed for a liquid fuel requiring a finite length of the combustor for complete evaporation. The substitution of a gaseous fuel greatly increased local fuel-air ratios in the upstream end of the combustor, where a relatively small amount of air is introduced, causing overenrichment and flame blow-out. The broader stability limits obtained with hydrogen (fig. 9) may be attributed, at least in part, to its wider flammability range. The lean-to-rich flammability range for propane is 2.1 to 9.4 percent by volume; corresponding values for hydrogen are 4.0 to 74.2 percent (ref. 6, pp. 749, 751).

Combustion Efficiency

Combustion efficiencies of 90 percent and higher were obtained with hydrogen fuel at pressures as low as 8.0 inches of mercury absolute. The highest efficiencies were observed at low values of temperature rise. This trend indicates that the primary combustion zone was operating overrich. More optimum conditions for combustion were obtained at low overall fuel-air ratios.

Combustion efficiencies of less than 100 percent were obtained at practically all conditions of operation. Losses in efficiency in turbojet combustors have been attributed to (1) insufficient residence time for evaporation, mixing, and combustion of the fuel and air, (2) quenching effects of the relatively cool combustor walls, and (3) impingement of liquid fuel on the walls (ref. 7). Hydrogen fuel has an extremely high flame speed (about 6 times that of propane, ref. 6, pp. 460, 468) and requires no vaporization. Also, of course, liquid fuel impingement on the walls has been eliminated. Losses in efficiencies are, therefore, most probably attributable to effects of wall quenching and insufficient mixing of the fuel and the air. Previous research (ref. 8) has indicated a relation between combustion efficiency and combustor size, as expressed by the hydraulic radius of the combustor liner at the plane where the undisturbed fuel spray would impinge upon the wall. This relation was attributed to some of the factors noted previously - fuel impingement, wall quenching, and fuel-air mixing patterns. For the combustor and the operating conditions used in the present tests, efficiencies of less than 100 percent would be predicted. 3614

From the preceding discussion, it would be expected that variations in injector design might affect combustion efficiency by affecting the rate of mixing of the fuel and air. Observed effects of variations in injector design on performance of hydrogen were relatively minor, and occurred principally at very low values of temperature rise. It must be concluded that the injectors investigated did not greatly alter mixing characteristics. Major changes in the air-introduction system might produce more pronounced effects on performance.

Relatively small variations in injector design produced very significant effects on the combustion efficiency of propane (fig. 9). The nozzle having the smaller orifices and hence the higher pressure differential gave higher efficiencies. In this case the variations in mixing characteristics were sufficient to cause marked changes in combustion performance of this less reactive fuel.

Considerably higher efficiencies were obtained with hydrogen than with propane (fig. 9). This result would be expected from previous research (ref. 5) indicating that higher combustion efficiencies may be obtained with fuels having higher flame speeds. Figure 9 also shows that the performance of hydrogen was much less affected by large increases in reference velocity than was that of propane. This is of importance when considering future development engines utilizing higher flow per unit area.

The effects of inlet-air pressure p_i, temperature T_i, and reference velocity V_r, expressed by the correlating parameter V_r/p_iT_i (ref. 2) on the combustion efficiencies of hydrogen and propane are shown in figure 10. Data are shown for values of combustor temperature rise of 680° F (fig. 10(a)) and 1180° F (fig. 10(b)), which correspond to cruise and

rated-speed requirements, respectively, of a representative turbojet engine (ref. 9). Hydrogen data obtained with injector B, the only one tested at all operating conditions, and propane data obtained with injector A, which produced the highest efficiencies, are shown in this comparison. With hydrogen, marked decreases in efficiency occur only at very high values of $V_r/p_i T_i$. The combustion efficiency of propane was adversely affected by increases in $V_r/p_i T_i$ even at low values of the
3614 correlating parameter. Also, combustion of propane was not possible at the higher value of temperature rise because of flame blow-out (fig. 9).

Curves representing combustion efficiencies obtained in the same tubular combustor with liquid MIL-F-5624A, grade JP-4 fuel (ref. 7) and in an experimental annular turbojet combustor with gaseous propane fuel (ref. 9) are included in figure 10. The liquid-fuel curve represents the performance of the tubular combustor as it is currently being used in service. Very large improvements in efficiency at severe operating conditions would be obtained through the use of gaseous hydrogen fuel in this combustor.

The experimental combustor curve shown in figure 10 is representative of the best performance that has been obtained in experimental combustors investigated at the NACA Lewis laboratory. At low values of $V_r/p_i T_i$ the experimental combustor produced near 100-percent combustion efficiency; however, the limited data indicate that the efficiency decreased more rapidly with an increase in $V_r/p_i T_i$ than did that of hydrogen. It is expected that a combination of a high-performance experimental combustor and a highly reactive fuel such as hydrogen would assure near 100-percent combustion efficiencies over a very broad range of operating conditions.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the performance of gaseous hydrogen fuel in a single tubular combustor operated at low inlet-air conditions:

1. Hydrogen fuel burned over very broad ranges of combustor temperature rise (or fuel-air ratio) at pressures as low as 3.3 inches of mercury absolute. No combustion instability or flame blow-out was observed within the ranges of fuel and air flow that were investigated.

2. At inlet-air pressures of 8.0 inches of mercury and above, combustion efficiencies in excess of 90 percent were maintained. At these pressures the effects of large increases in reference air velocity on combustion efficiency were relatively minor. At pressures below 8.0 inches of mercury absolute, marked decreases in combustion efficiency were observed.

3. The combustion performance of hydrogen was not significantly affected by variations in the design of the fuel injector.

4. In comparison, a gaseous hydrocarbon fuel, propane, burned over only very limited ranges of temperature rise. Combustion efficiencies were lower and were very adversely affected by increases in reference velocity and decreases in inlet-air pressure to 8.0 inches of mercury absolute.

5. The superior performance of hydrogen fuel is attributed to its higher flame speed and its wider flammability range. The fact that 100-percent combustion efficiency was not obtained over a broad range of operating conditions is attributed to limited mixing of the fuel and air in the primary zone of the combustor used for these tests. 3614

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 23, 1954

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TABLE I. - HYDROGEN PERFORMANCE DATA

(a) Injector A

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
1	8.0	40	0.564	100.7	9.60	0.00473	875	835	88.0	26.4
2		41	.564	100.9	13.49	.00665	1122	1081	83.4	37.4
3		40	.563	100.5	16.38	.00808	1322	1282	83.3	45.4
4		39	.561	100.0	20.79	.01029	1535	1496	79.0	59.4
5		38	.564	100.3	21.83	.01075	1705	1667	85.4	62.4
6		44	.560	100.8	1.43	.00071	193	149	96.7	1.0
7		41	.559	100.0	7.02	.00349	700	659	91.8	17.4
8		40	.562	100.2	1.84	.00091	223	183	93.2	1.5
9		41	.562	100.4	3.98	.00197	424	383	92.4	7.9
10		40	.562	100.2	11.62	.00574	1090	1050	93.1	31.4
11		52	.562	102.7	1.80	.00089	222	170	88.7	2.0
12		48	.560	101.6	5.73	.00284	593	545	92.0	12.4
13		47	.564	102.1	13.91	.00685	1210	1163	87.8	37.4
14		207	.562	134.3	9.85	.00487	1025	818	84.7	26.4
15		199	.560	132.3	14.41	.00715	1313	1114	81.3	41.4
16		191	.560	130.7	18.74	.00930	1542	1351	78.4	54.4
17		203	.561	133.3	21.12	.01046	1624	1421	74.4	61.4
18		198	.562	132.5	1.15	.00057	311	113	95.2	.5
19		202	.562	133.3	7.95	.00393	876	674	84.8	20.4
20		196	.568	133.5	17.46	.00854	1505	1309	81.9	48.4
21		201	.557	131.9	8.58	.00428	960	759	88.6	22.4
22		204	.571	135.8	12.76	.00620	1300	1096	91.6	35.4
23		199	.565	133.3	13.90	.00683	1358	1159	88.7	39.4
24		199	.563	132.8	8.72	.00430	978	779	90.4	22.4
25		206	.562	134.0	2.20	.00109	415	209	90.7	3.2
26		40	.735	132.2	10.65	.00402	825	785	96.3	28.4
27		39	.735	131.9	13.91	.00526	1000	961	92.1	38.4
28		45	.732	133.1	18.17	.00690	1234	1189	89.3	51.4
29		36	.738	131.8	20.85	.00785	1375	1339	89.7	59.4
30		202	.735	176.0	4.80	.00181	540	338	89.1	10.4
31		193	.738	174.3	9.41	.00354	825	632	87.8	25.4
32	8.1	202	0.727	171.8	15.20	0.00581	1180	978	85.9	42.3
33	8.0	218	0.730	179.2	10.90	0.00415	925	707	84.5	30.4
34		178	.729	168.3	14.81	.00564	1110	932	84.0	42.4
35	8.4	199	0.729	165.4	20.41	0.00778	1390	1191	80.8	59.2
36	8.0	197	0.733	174.4	2.16	0.00082	355	158	90.6	2.5
37		199	.732	174.7	13.52	.00513	1085	886	87.6	37.4
38	6.2	35	0.491	112.3	3.07	0.00174	358	323	87.5	5.8
39		35	.491	112.3	8.80	.00498	922	887	89.0	23.8
40		42	.495	114.9	3.30	.00185	394	352	90.7	6.8
41		40	.500	115.6	9.25	.00514	962	922	90.0	25.3
42		41	.501	116.0	1.78	.00099	225	184	86.8	2.4
43		40	.500	115.6	6.65	.00369	722	682	90.5	17.3
44		38	.505	116.2	17.40	.00957	1532	1494	84.4	46.3
45	3.3	52	0.151	66.48	1.50	0.00276	525	473	82.2	2.8
46		51	.151	66.35	2.68	.00493	823	772	77.9	6.3
47		50	.152	66.66	5.51	.01007	1425	1175	73.4	14.7
48		50	.152	66.66	8.02	.01466	1870	1820	71.4	22.7
49		61	.154	68.99	2.13	.00385	711	650	82.6	4.3
50		60	.156	69.75	5.17	.00919	1385	1325	76.9	13.7
51		60	.158	70.65	7.20	.01266	1741	1681	74.6	19.7
52		200	.150	85.13	1.48	.00274	616	416	72.5	3.3
53		202	.150	85.39	3.54	.00619	1070	868	71.5	10.3
54		209	.150	86.29	5.50	.01019	1523	1314	70.1	14.7
55		204	.154	87.93	6.98	.01260	1805	1601	71.5	19.7
56		203	.154	87.80	1.45	.00262	599	396	72.5	3.3
57		199	.154	87.27	3.51	.00633	1100	1001	72.8	9.2
58		200	.152	86.26	6.62	.01210	1730	1530	71.5	18.7

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TABLE I. - Continued. HYDROGEN PERFORMANCE DATA

(b) Injector B.

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
59	14.3	46	0.794	79.9	9.54	0.00334	716	670	97.6	5.3
60		39	.800	79.4	14.79	.00514	1003	964	94.7	11.3
61		40	.799	79.4	18.89	.00657	1210	1170	92.0	16.3
62		46	.801	80.6	28.45	.00986	1630	1584	87.4	27.3
63		46	.798	80.3	38.09	.01326	2005	1959	84.5	38.3
64		199	.800	105.1	9.78	.00340	851	652	94.5	5.3
65		200	.799	105.1	16.28	.00566	1208	1008	91.5	12.3
66		201	.799	105.3	23.55	.00819	1545	1344	87.9	21.3
67		210	.800	106.9	30.59	.01062	1812	1602	83.7	30.3
68		198	.799	104.8	36.39	.01265	2040	1842	83.4	36.3
69		46	.999	100.9	9.91	.00276	600	554	96.4	4.8
70		41	.999	99.9	17.28	.00481	955	914	95.1	14.3
71		38	.998	99.2	26.76	.00745	1345	1307	91.8	25.3
72		44	.998	100.4	35.27	.00982	1646	1602	88.8	34.3
73		43	1.001	100.5	47.50	.01318	2010	1967	85.3	49.3
74		40	.997	99.5	1.84	.00051	147	107	95.5	----
75		40	.995	99.3	5.20	.00145	340	300	97.5	.9
76		40	.992	99.0	9.82	.0C275	586	546	95.6	4.8
77		41	.992	99.2	14.65	.00410	814	773	93.2	10.3
78		205	.994	132.5	9.84	.00275	760	555	98.2	5.3
79		210	.993	133.3	15.58	.00436	1016	806	93.0	12.3
80		207	.998	133.4	23.28	.00648	1340	1133	90.9	21.3
81		208	.999	133.7	32.01	.00890	1646	1438	87.5	31.3
82		196	.999	131.3	44.28	.01231	2025	1829	84.8	45.3
83		198	1.000	131.9	1.85	.00051	300	102	92.5	----
84		202	.999	132.5	4.92	.00137	467	265	93.3	.4
85		194	1.000	131.1	9.82	.00273	732	538	95.4	5.3
86		202	.998	132.4	16.93	.00471	1045	843	90.3	13.3
87		37	1.298	129.5	10.17	.00218	481	444	97.4	5.3
88		42	1.298	130.8	19.96	.00427	870	828	96.0	17.3
89		38	1.298	129.8	30.19	.00646	1205	1167	93.2	29.3
90		43	1.298	131.1	46.62	.00998	1665	1622	88.7	48.3
91		38	1.301	130.4	1.68	.00036	115	77	96.8	----
92		40	1.300	130.8	4.93	.00105	250	210	92.4	.4
93		40	1.300	130.8	8.09	.00173	405	365	100.3	3.3
94		40	1.299	130.7	15.23	.00326	680	640	95.3	10.3
95		204	1.302	175.2	9.83	.00210	620	416	94.5	5.3
96		198	1.303	173.6	14.92	.00318	805	607	93.5	11.3
97		180	1.307	169.4	22.46	.00477	1060	880	93.1	20.3
98		195	1.315	174.5	28.48	.00602	1255	1060	91.0	27.3
99		205	1.306	176.0	34.23	.00728	1440	1235	89.6	34.3
100		199	1.308	174.6	35.12	.00746	1465	1266	89.8	35.3
101		194	1.300	171.6	5.05	.00108	411	217	94.4	.4
102		194	1.296	171.6	2.07	.00044	285	91	96.5	----
103		198	1.295	172.5	16.01	.00343	847	649	92.9	11.3
104	8.0	45	0.562	101.3	10.89	0.00538	1005	960	90.1	8.9
105		42	.561	100.6	15.50	.00767	1327	1285	87.6	14.4
106		40	.561	100.3	19.79	.00980	1597	1557	86.3	20.4
107		40	.562	100.3	24.56	.01214	1852	1812	83.9	26.4
108		49	.560	101.8	27.88	.01383	2070	2021	84.4	29.4
109		42	.567	101.6	1.70	.00083	212	170	93.7	----
110		40	.566	101.1	5.00	.00245	507	467	91.1	1.0
111		40	.565	100.9	8.80	.00433	845	805	92.4	6.9
112		40	.564	100.7	14.78	.00728	1221	1181	84.2	13.4
113		41	.563	100.6	2.66	.00131	290	249	89.5	.1
114		37	.564	99.99	5.18	.00255	524	487	91.7	2.0
115		38	.560	99.49	9.67	.00480	931	893	93.0	7.9
116		38	.560	99.49	17.43	.00864	1402	1364	84.3	15.9
117		37	.561	99.46	13.22	.00654	1149	1102	87.3	11.4
118		39	.558	99.32	7.46	.00371	744	705	93.0	4.7

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TABLE I. - Continued. HYDROGEN PERFORMANCE DATA

(b) Injector B - concluded

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
119	8.0	188	0.563	130.7	12.26	0.00605	1238	1050	89.5	11.4
120		198	.562	132.5	16.55	.00818	1525	1327	86.3	16.4
121		197	.567	133.5	22.20	.01088	1822	1625	83.2	23.4
122		198	.566	133.5	25.44	.01248	2033	1835	84.0	27.4
123		200	.562	132.9	1.12	.00055	312	112	94.0	----
124		211	.561	134.9	3.22	.00160	499	288	85.4	.5
125		200	.561	132.7	5.03	.00249	668	468	90.7	2.5
126		210	.560	134.5	8.89	.00441	990	780	88.6	6.9
127		198	.560	132.1	14.53	.00721	1344	1146	83.2	12.4
128		200	.559	132.1	2.23	.00111	405	205	87.4	----
129		194	.560	131.1	7.12	.00353	835	641	89.2	4.5
130		199	.560	132.1	13.52	.00670	1282	1083	83.9	11.9
131		200	.561	132.6	16.79	.00831	1519	1319	84.7	15.9
132		46	.730	133.0	11.24	.00428	866	820	95.0	9.4
133		42	.730	131.9	16.21	.00617	1151	1109	92.1	15.4
134		44	.729	132.3	21.75	.00829	1438	1394	89.2	22.4
135		38	.728	130.4	1.79	.00068	185	147	100.6	----
136		39	.729	130.9	5.28	.00201	440	401	94.7	2.5
137		42	.730	131.8	9.38	.00357	733	691	94.8	7.4
138		40	.730	131.3	14.59	.00555	1014	974	88.7	13.4
139		200	.735	175.8	12.30	.00465	1068	868	94.2	11.4
140		190	.735	173.0	16.36	.00618	1275	1085	90.7	16.4
141		211	.736	179.0	3.02	.00114	422	211	88.1	.1
142		198	.738	175.8	4.91	.00185	551	353	91.2	2.0
143		202	.734	176.1	9.12	.00345	826	624	89.2	6.9
144		204	.733	176.4	14.72	.00558	1125	921	84.0	13.4
145	6.2	44	0.501	116.7	1.56	0.00086	221	177	94.8	----
146		48	.502	117.9	6.74	.00373	709	661	86.2	4.8
147		.47	.501	117.4	17.21	.00954	1525	1478	83.6	17.3
148		39	.498	114.9	3.00	.00167	361	322	85.1	.9
149		38	.494	113.7	9.45	.00531	970	932	88.1	8.3
150		203	.500	154.0	1.76	.00098	377	174	84.7	----
151		202	.501	154.0	5.24	.00290	708	506	84.4	2.9
152		198	.502	153.4	11.58	.00641	1240	1042	83.8	10.7
153		198	.501	153.1	18.01	.00998	1649	1451	79.4	17.3
154	3.3	56	0.146	64.8	1.50	0.00285	556	500	83.5	0.4
155		57	.146	64.9	3.35	.00637	985	928	73.9	1.9
156		58	.145	64.6	6.04	.01157	1537	1479	70.0	5.3
157		50	.149	65.3	2.01	.00375	633	583	75.1	.9
158		50	.149	65.3	3.68	.00687	1035	985	73.3	2.4
159		50	.149	65.3	5.81	.01084	1457	1407	70.3	4.8
160		45	.150	65.1	1.80	.00334	595	550	79.1	.9
161		44	.150	65.0	3.62	.00671	1009	965	73.2	2.8
162		43	.151	65.3	6.39	.01175	1540	1497	70.0	5.8
163		40	.152	65.4	9.38	.01714	2030	1990	68.5	9.2
164		209	.148	85.1	1.93	.00362	735	526	70.8	.9
165		214	.145	84.0	4.54	.00870	1325	1101	67.5	3.3
166		198	.149	84.3	1.83	.00340	726	528	75.3	.9
167		200	.145	82.3	3.73	.00714	1179	979	71.0	2.4
168		201	.149	84.7	5.64	.01053	1530	1329	68.7	4.8
169		200	.150	85.1	8.31	.01539	1981	1781	67.4	8.2
170		200	.149	84.6	4.61	.00860	1358	1158	71.3	3.8
171		202	.149	84.8	1.95	.00364	795	593	79.5	.4
172		199	.149	84.4	1.12	.00209	571	372	84.7	.4
173		196	.150	84.6	1.88	.00349	745	549	76.2	1.4
174		203	.150	85.5	3.07	.00568	1024	821	73.0	1.9
175		201	.154	87.5	6.10	.01101	1550	1349	67.0	5.8
176		200	.154	87.4	3.0	.00541	1003	803	75.1	2.1

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TABLE I. - Continued. HYDROGEN PERFORMANCE DATA

(c) Injector C

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
177	14.3	40	0.802	79.8	11.30	0.00391	785	745	93.7	2.4
178		40	.796	79.1	16.55	.00577	1111	1071	94.6	5.3
179		42	.794	79.3	24.26	.00849	1515	1473	92.7	10.3
180		48	.799	80.7	32.83	.01142	1875	1827	89.5	16.3
181		42	.799	79.8	37.60	.01307	2055	2013	88.3	20.3
182		197	.796	104.3	11.05	.00386	908	711	91.2	1.9
183		205	.796	105.5	17.64	.00615	1265	1060	89.1	6.3
184		206	.795	105.6	25.98	.00908	1615	1409	84.1	12.3
185		197	.797	104.4	36.28	.01265	2025	1828	82.7	19.3
186		45	1.002	101.0	12.79	.00355	770	725	99.9	2.8
187		40	1.000	99.8	19.20	.00533	1045	1005	95.4	6.8
188		40	1.000	100.0	26.16	.00727	1355	1315	94.7	12.3
189		38	1.002	99.6	34.75	.00963	1660	1622	91.6	17.3
190		42	.993	99.5	45.12	.01262	2025	1983	89.7	25.3
191		40	.994	99.2	1.11	.00031	106	66	96.9	----
192		40	.994	99.2	5.43	.00152	350	310	96.8	----
193		44	.996	100.2	11.43	.00319	680	636	97.0	2.4
194		42	1.000	100.2	18.55	.00515	998	956	93.6	5.8
195		203	.999	132.7	11.03	.00307	800	597	94.9	2.4
196		193	1.000	130.9	18.53	.00515	1124	931	91.8	6.8
197		202	.999	132.5	27.97	.00778	1493	1291	88.2	13.3
198		195	.999	131.1	36.35	.01011	1780	1585	86.6	19.3
199		197	1.000	131.7	43.72	.01214	2020	1823	85.5	24.3
200		199	1.000	132.1	2.58	.00072	345	146	95.4	----
201		195	.999	131.1	4.91	.00137	465	270	92.8	----
202		198	.999	131.1	7.66	.00213	618	420	93.8	----
203		194	.998	130.8	15.97	.00440	988	794	90.4	4.3
204		194	.999	130.9	17.63	.00490	1040	846	87.0	5.3
205		43	1.291	130.7	12.71	.00273	612	569	100.1	2.8
206		42	1.290	130.3	21.60	.00465	943	901	96.7	8.3
207		37	1.307	130.7	30.73	.00653	1244	1207	95.6	14.3
208		44	1.290	130.8	40.79	.00878	1565	1521	93.2	22.3
209		43	1.298	131.1	46.71	.01000	1730	1687	92.5	26.3
210		40	1.300	130.8	2.02	.00043	130	90	101.4	----
211		41	1.306	131.7	5.25	.00112	275	234	97.8	----
212		41	1.306	131.7	9.92	.00211	478	437	99.0	1.4
213		40	1.305	131.3	17.93	.00382	743	703	90.1	2.8
214		215	1.295	177.0	11.39	.00244	692	477	94.5	1.9
215		206	1.295	174.7	20.81	.00446	1016	810	91.3	8.3
216		198	1.295	172.6	29.64	.00636	1285	1087	88.4	14.3
217		202	1.295	173.6	37.44	.00803	1517	1315	87.3	20.3
218		196	1.300	172.6	2.49	.00053	304	108	97.4	----
219		196	1.297	172.2	5.00	.00107	400	204	89.5	----
220		196	1.300	172.6	7.43	.00159	512	316	94.0	----
221		196	1.299	172.5	10.77	.00230	650	454	94.7	1.4
222		194	1.309	173.4	15.32	.00325	795	601	89.8	3.8

[redacted]

TABLE I. - Concluded. HYDROGEN PERFORMANCE DATA

(d) Injector D

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
223	14.3	202	1.300	174.2	1.86	0.00040	273	71	81.6	----
224		202	1.304	174.8	4.93	.00105	402	200	93.7	0.4
225		198	1.306	174.0	8.96	.00191	570	372	92.5	4.3
226		198	1.305	173.8	16.55	.00352	830	639	88.4	13.31
227	6.2	42	0.491	114.0	1.31	0.00074	200	158	100.0	----
228		40	.491	113.5	4.88	.00276	575	535	93.2	2.4
229		38	.491	113.2	8.82	.00499	961	923	92.9	7.3
230		37	.490	112.6	16.85	.00955	1565	1528	86.8	16.3
231		38	.496	114.0	2.03	.00114	260	222	91.8	.2
232		38	.501	115.3	1.83	.00102	230	192	88.0	.2
233		38	.501	115.3	5.01	.00277	545	507	87.4	2.6
234		40	.504	116.3	8.82	.00486	908	868	89.4	7.5
235		42	.502	116.5	12.56	.00695	1218	1176	87.0	11.0
236		208	.497	154.2	1.44	.00081	360	152	90.1	----
237		194	.496	150.7	4.18	.00234	625	431	88.0	1.9
238		203	.491	151.2	8.33	.00471	1048	845	90.4	7.3
239		203	.491	151.2	15.79	.00893	1620	1417	86.0	15.3
240	3.3	60	0.147	65.7	1.24	0.00235	492	432	87.4	----
241		60	.142	63.5	2.95	.00573	928	868	76.1	1.4
242		58	.145	64.6	4.99	.00956	1425	1367	76.6	3.8
243		57	.146	64.9	8.38	.01593	1993	1936	71.4	8.7
244		48	.151	66.0	2.61	.00481	852	804	83.2	1.4
245		48	.151	66.0	4.52	.00831	1310	1262	79.8	3.3
246		47	.151	65.8	6.10	.01122	1650	1603	78.7	5.3
247		157	.146	77.4	7.89	.01499	2015	1858	72.2	7.7
248		156	.145	76.8	5.49	.01051	1595	1439	74.8	4.3
249		169	.145	78.4	3.35	.00643	1160	991	79.3	2.1
250		176	.144	78.7	1.43	.00275	660	484	84.5	.4
251		199	.148	83.9	1.71	.00322	690	491	73.7	1.1
252		200	.148	84.0	3.33	.00625	1125	925	75.6	2.1
253		202	.148	84.3	4.97	.00933	1468	1266	72.8	4.1
254		202	.148	84.3	8.06	.01512	2010	1808	69.6	8.0

(e) Injector E

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
255	14.3	197	1.306	173.6	2.14	0.00046	269	72	73.0	----
256		197	1.305	173.6	5.47	.00116	420	223	91.0	1.4
257		192	1.305	172.3	9.78	.00208	605	413	95.2	6.3
258		196	1.310	174.0	16.40	.00348	835	639	90.5	14.3
259	6.2	31	0.499	113.3	1.36	0.00076	180	149	93.3	----
260		37	.502	115.3	4.56	.00252	510	473	89.9	2.9
261		40	.502	116.0	9.73	.00538	1000	960	90.4	9.2
262		41	.500	115.8	17.78	.00988	1585	1544	84.8	18.3
263	3.3	46	0.147	63.9	1.38	0.00261	562	516	94.4	0.4
264		46	.147	63.9	3.42	.00647	1011	965	76.1	2.4
265		45	.146	63.4	5.76	.01095	1485	1440	71.6	5.8
266		46	.148	64.4	8.70	.01632	2000	1954	70.2	10.2
267		185	.150	83.2	1.24	.00230	620	435	90.1	.4
268		188	.150	83.5	3.23	.00598	1022	834	70.8	2.8
269		191	.151	84.5	6.02	.01107	1598	1407	69.6	6.3
270		191	.146	81.7	8.34	.01586	2008	1817	67.1	9.7

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TABLE II. - PROPANE PERFORMANCE DATA

(a) Injector A

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
271	14.3	36	0.802	79.2	18.62	0.00645	500	464	89.0	6.8
272		37	.802	79.3	32.83	.01137	895	858	96.5	18.3
273		42	.800	79.9	41.37	.01436	1030	988	89.5	23.3
274		41	.800	-----	45.28	.01572	[a]1050	1009	83.8	24.3
275		196	.801	104.8	24.08	.00835	840	644	98.7	12.3
276		196	.801	104.8	37.85	.01312	1120	924	92.9	21.3
277		200	.805	105.9	50.45	.01741	1250	1050	81.2	29.8
278		195	.989	129.7	20.11	.00565	605	410	90.9	8.7
279		194	.993	130.1	27.68	.00774	735	541	88.7	14.3
280		200	.993	131.3	33.65	.00941	875	675	92.3	18.8
281		203	.994	132.0	59.92	.01675	1125	922	73.5	35.3
282		190	1.293	170.1	18.09	.00389	420	230	73.1	7.3
283		200	1.303	174.2	34.03	.00725	660	460	80.1	19.3
284		200	1.297	173.4	46.31	.00992	770	570	73.6	27.2
285		197	1.293	172.0	53.26	.01144	745	548	61.6	32.1
286		198	1.298	173.0	63.94	.01368	740	542	51.2	39.1
287		201	1.298	173.8	21.02	.00450	460	259	71.5	9.8
288		201	1.300	173.9	34.70	.00742	660	459	78.3	19.3
289		200	1.305	174.3	51.03	.01086	800	600	71.1	29.0
290	8.0	205	0.555	132.3	13.90	0.00696	645	440	79.8	6.4
291		199	.558	131.8	19.39	.00965	820	621	82.6	12.3
292		204	.561	133.5	25.61	.01268	825	621	63.5	15.9
293		203	.552	-----	29.07	.01463	[a]790	587	52.2	18.4

(b) Injector B

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Mean temperature rise through combustor, °F	Combustion efficiency, percent	Fuel injector pressure drop, lb/sq in. gage
294	14.3	40	0.800	------	16.23	0.00564	380	340	74.0	0.4
295		43	.805	80.52	22.35	.00771	555	512	82.6	1.1
296		43	.803	80.32	29.50	.01020	700	657	81.2	2.4
297		39	.799	------	46.38	.01613	[a]995	956	77.2	5.8
298		195	.793	103.5	17.31	.00606	615	420	87.0	.6
299		200	.797	104.8	22.42	.00781	755	555	90.4	1.4
300		192	.798	103.7	30.52	.01062	935	743	90.6	2.8
301		201	.798	105.1	37.06	.01290	1075	874	89.1	4.3
302		196	.797	-----	53.59	.01868	[a]1280	1084	78.5	6.3
303		211	1.007	135.3	18.27	.00504	535	324	80.3	.6
304		208	1.002	133.9	34.42	.00954	790	582	78.2	3.8
305		210	.998	133.9	47.23	.01315	965	755	75.2	7.0
306		194	.998	-----	61.87	.01722	[a]1025	831	64.0	10.8
307		205	1.309	176.2	18.39	.00390	410	205	65.1	----
308		208	1.298	175.7	37.02	.00792	595	387	61.8	3.8
309		164	1.298	164.0	57.82	.01237	670	506	52.3	9.3
310		210	1.303	176.7	57.39	.01223	695	485	51.1	9.3
311		219	1.302	-----	65.66	.01401	[a]695	476	44.0	12.3
312	8.0	204	0.560	133.1	16.92	0.00839	635	431	65.1	1.5
313		203	.553	-----	19.80	.00994	700	497	63.9	2.7
314		200	.551	-----	-----	------	[a]750	550	----	----
315		200	.552	-----	27.65	.01392	775	575	53.6	4.5
316		200	.748	179.1	15.91	.00591	415	215	45.4	1.0
317		198	.748	178.4	20.35	.00756	450	252	41.8	2.0
318		195	.748	177.7	24.70	.00917	460	265	36.5	3.5
319		193	.749	-----	27.93	.01036	[a]460	267	32.6	4.5

[a]Blow-out.

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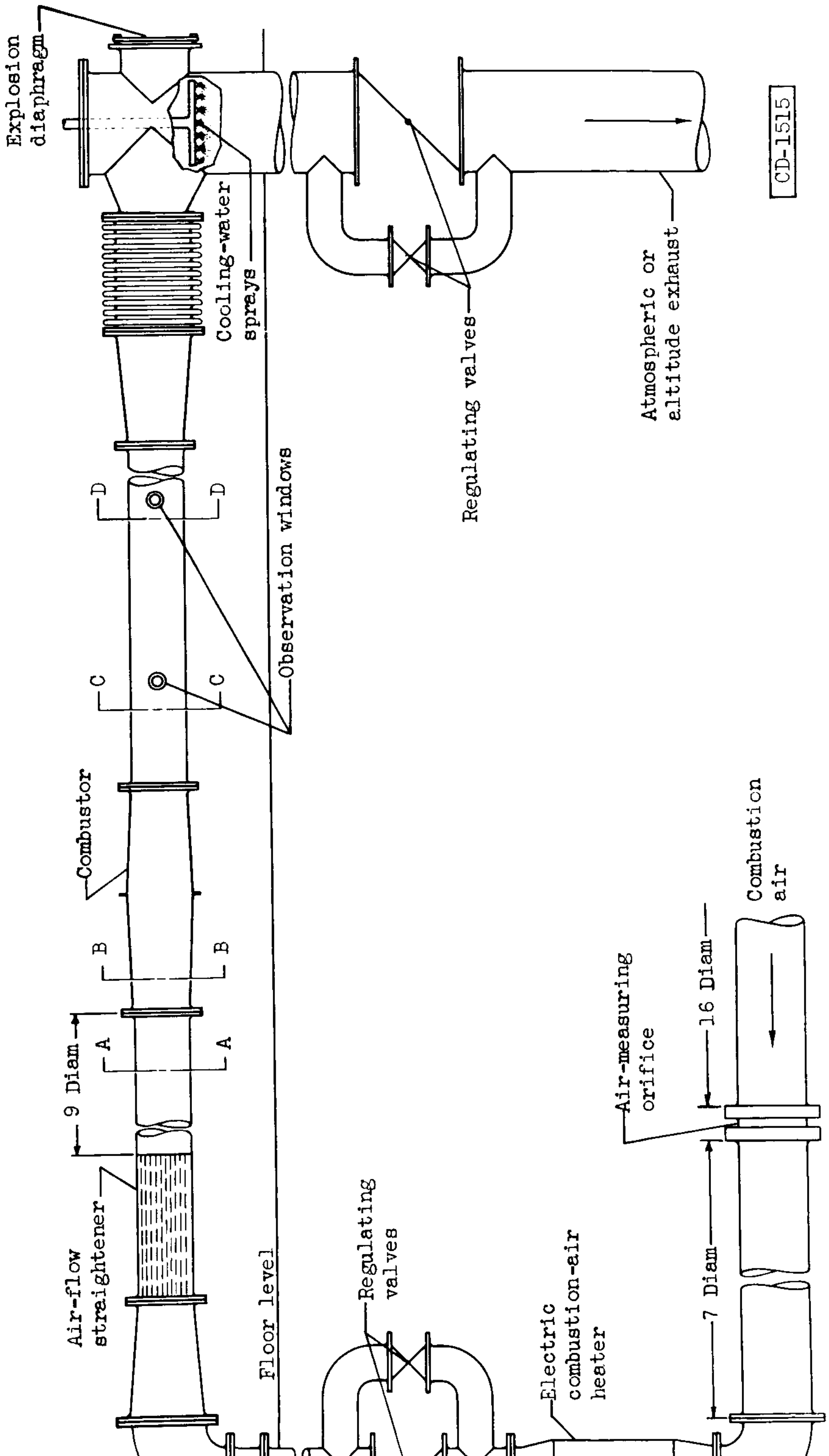

Figure 1. - Single-combustor installation and auxiliary equipment. Instrumentation planes, A-A, B-B, C-C, and D-D.

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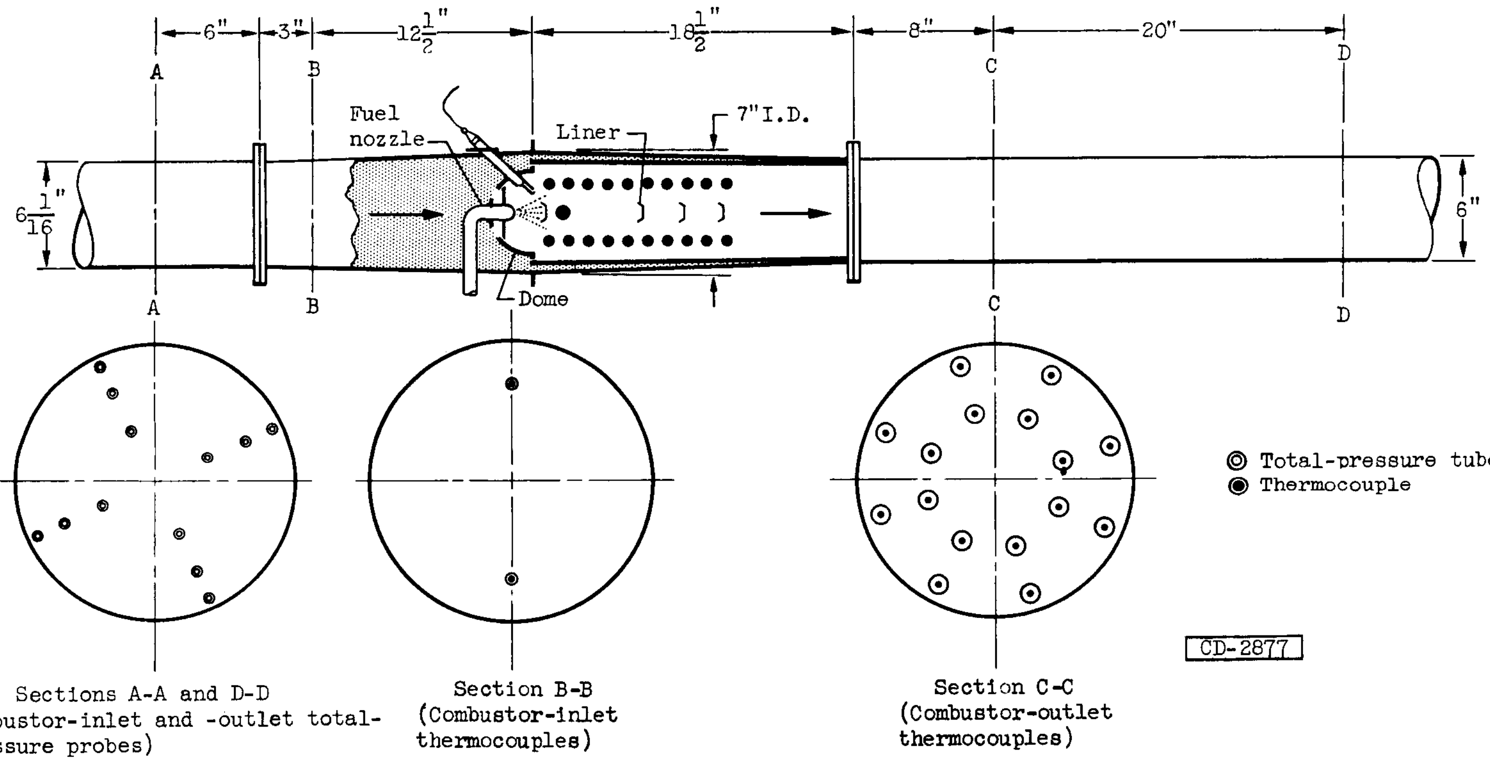

Figure 2. - Cross section of single-combustor installation showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes.

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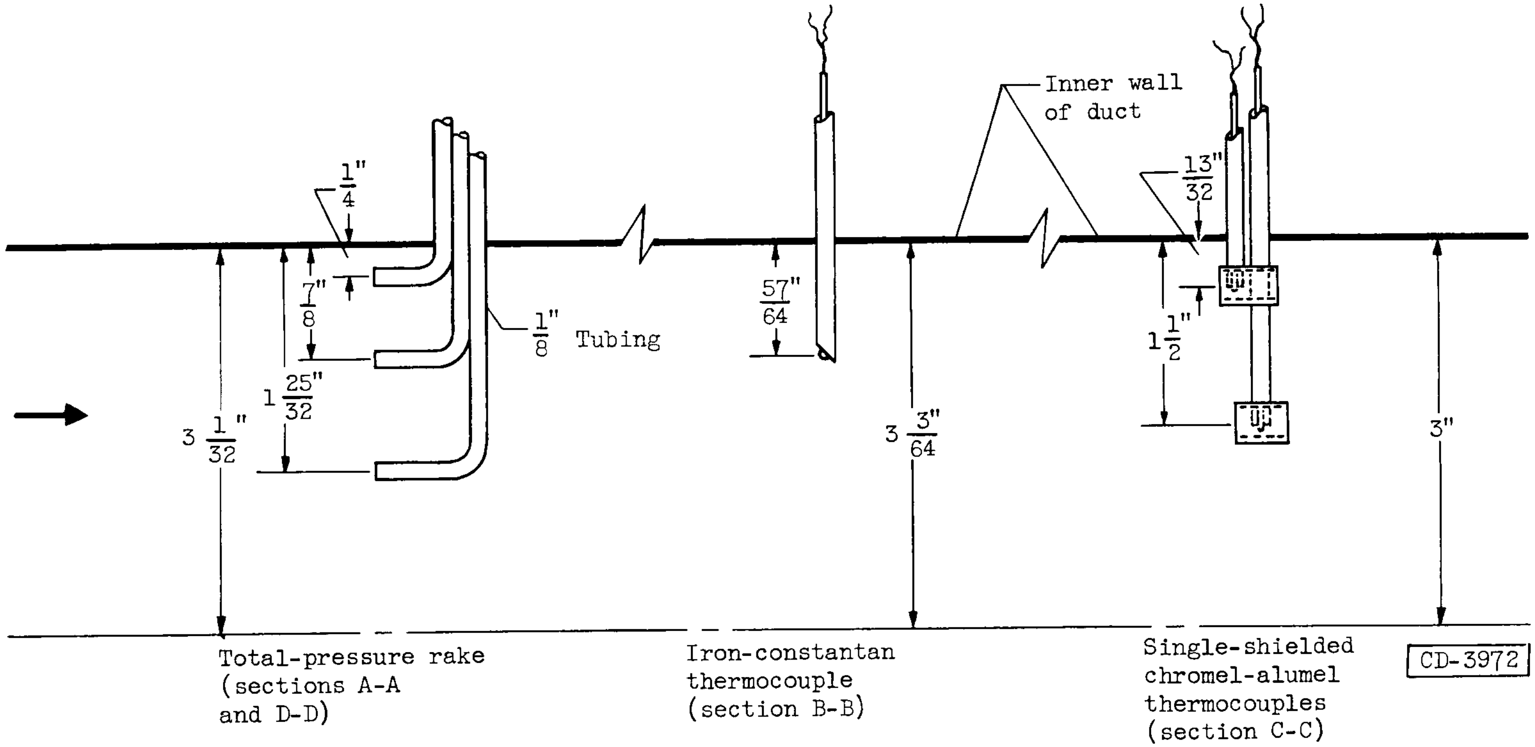

Figure 3. - Construction details of temperature- and pressure-measuring instruments.

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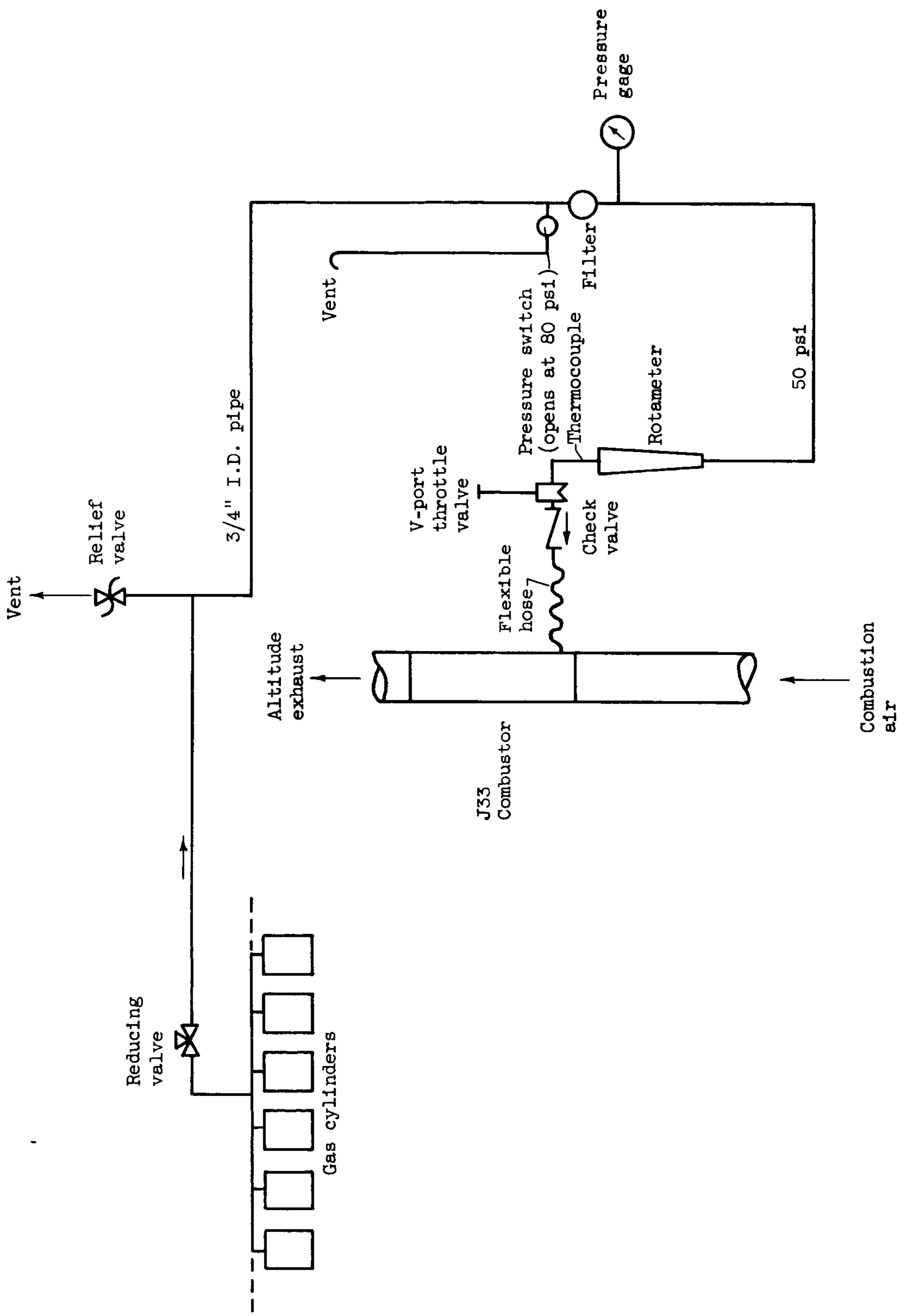

Figure 4. - Schematic diagram of gaseous fuel system.

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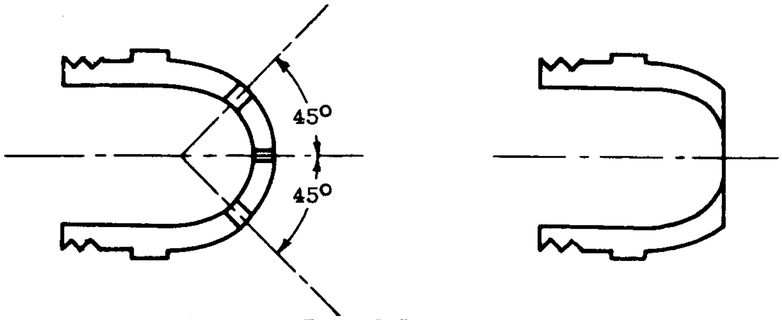
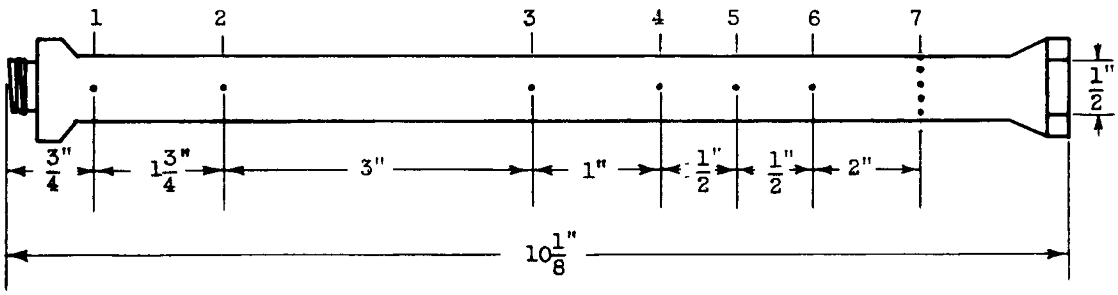


Injector configurations A, B, and C   Injector configuration D

Injector configuration	Number of holes	Hole diameter, in.	Total open hole area, sq in.
A	1	0.0160	0.0187
	6	0.06250	
B	1	0.0160	0.0417
	6	0.0938	
C	1	0.0160	0.0737
	6	0.125	
D	1	0.238	0.0445

(a) Injector configurations A, B, C, and D.



Station	Number of holes	Hole diameter, in.	Station hole area, sq in.	Total open hole area, sq in.
1	3	0.0520	0.00636	0.0490
2	4	.0350	.00385	
3	3	.0520	.00636	
4	3	.0520	.00636	
5	2	.0200	.00062	
6	3	.0520	.00636	
7	9	.0520	.01908	

(b) Injector configuration E.

Figure 5. - Fuel injectors.

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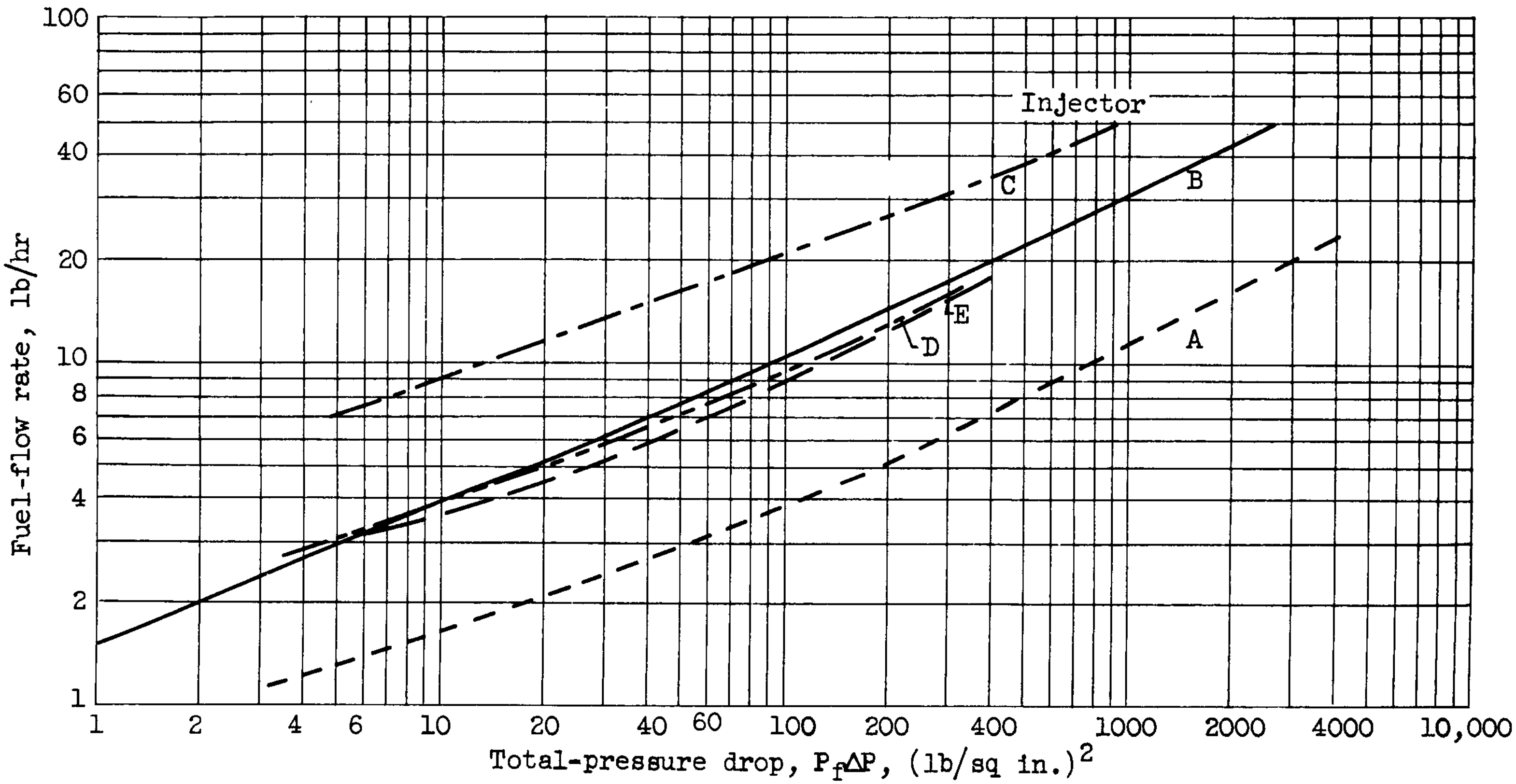
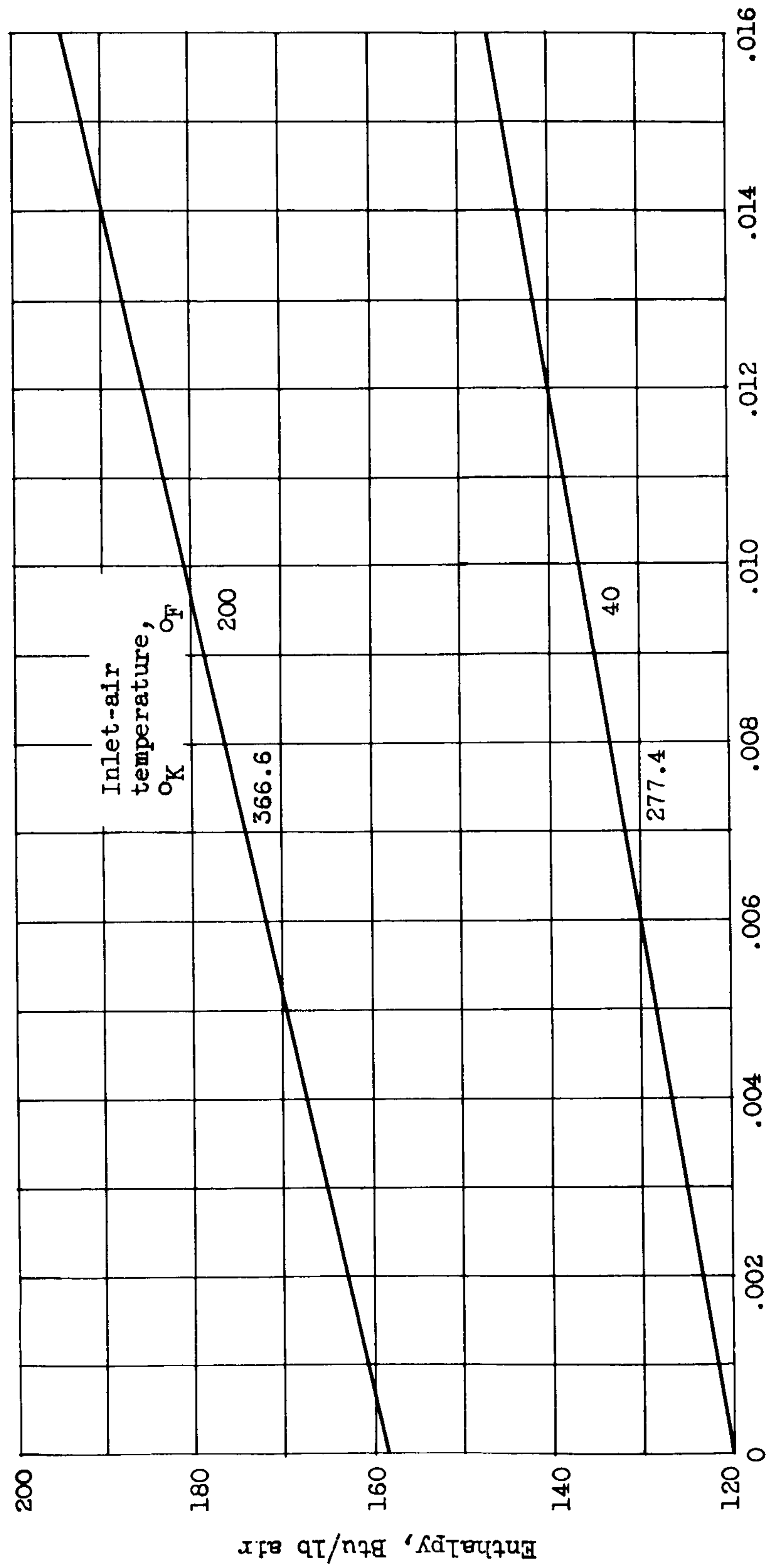


Figure 6. - Relation between fuel-flow rate and $P_f \Delta P$ (where P_f is fuel pressure and ΔP is injector pressure differential) for gaseous-fuel injectors.



(a) Inlet hydrogen-air mixture.

Figure 7. - Enthalpies of hydrogen-air mixtures and products of combustion.

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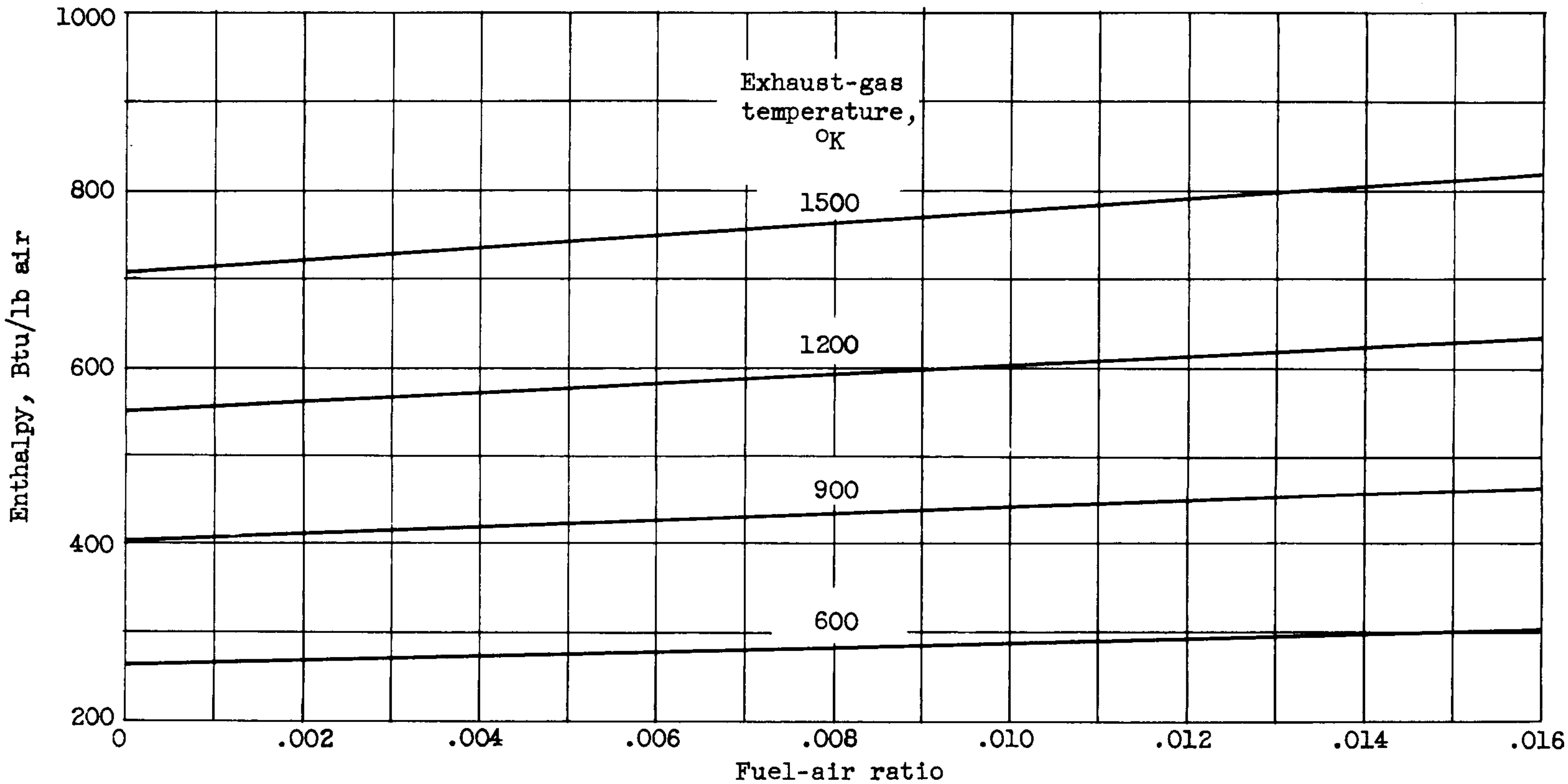
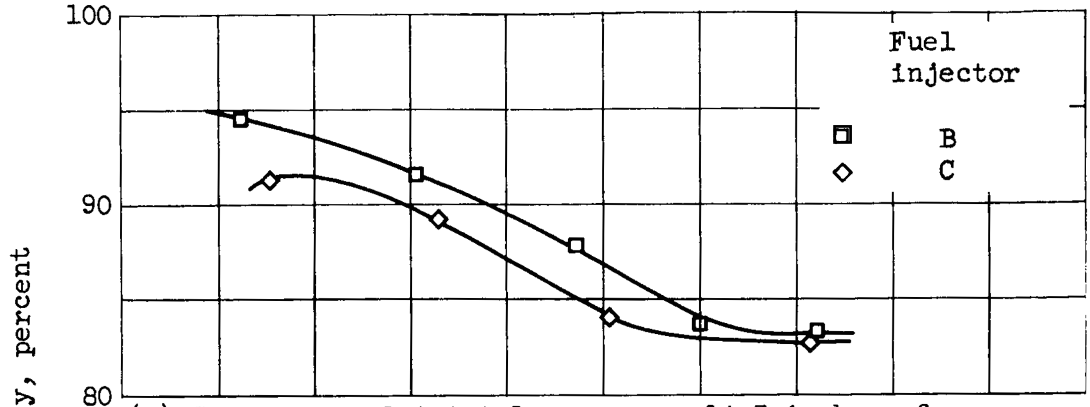
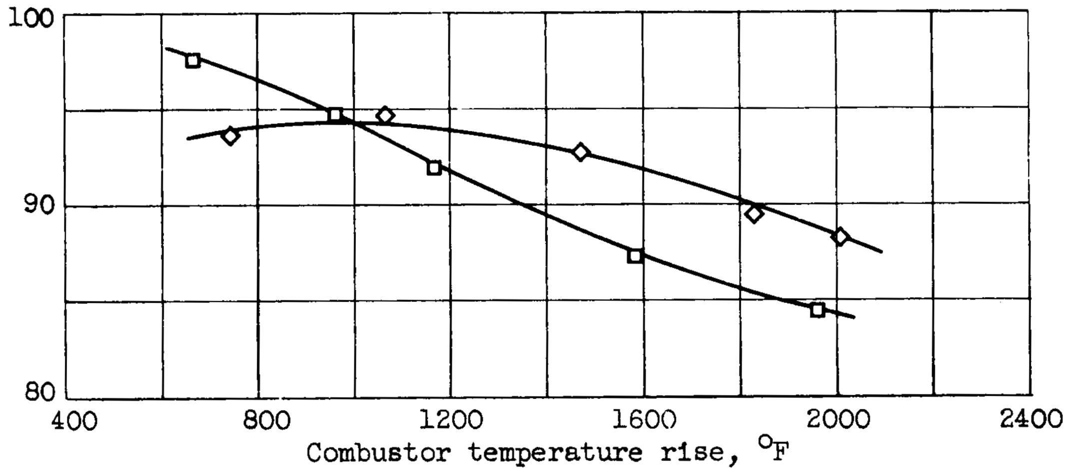


(b) Products of combustion of hydrogen and air.

Figure 7. - Concluded. Enthalpies of hydrogen-air mixtures and products of combustion.



(a) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 0.8 pound per second; inlet-air temperature, 200° F; reference velocity, 105 feet per second.



(b) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 0.8 pound per second; inlet-air temperature, 40° F; reference velocity, 80 feet per second.

Figure 8. - Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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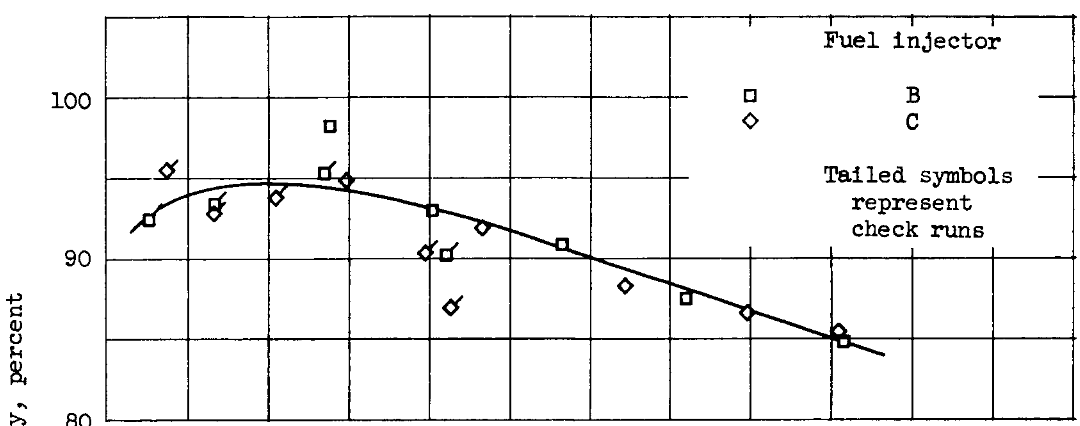
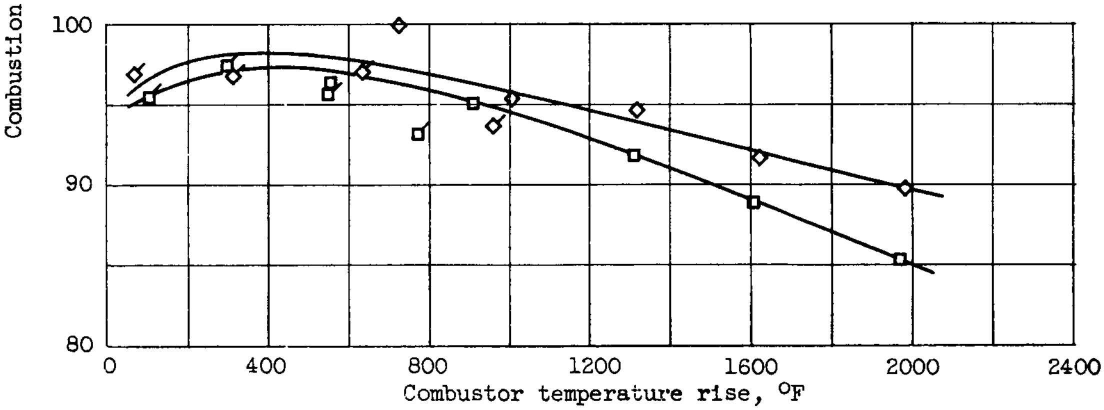


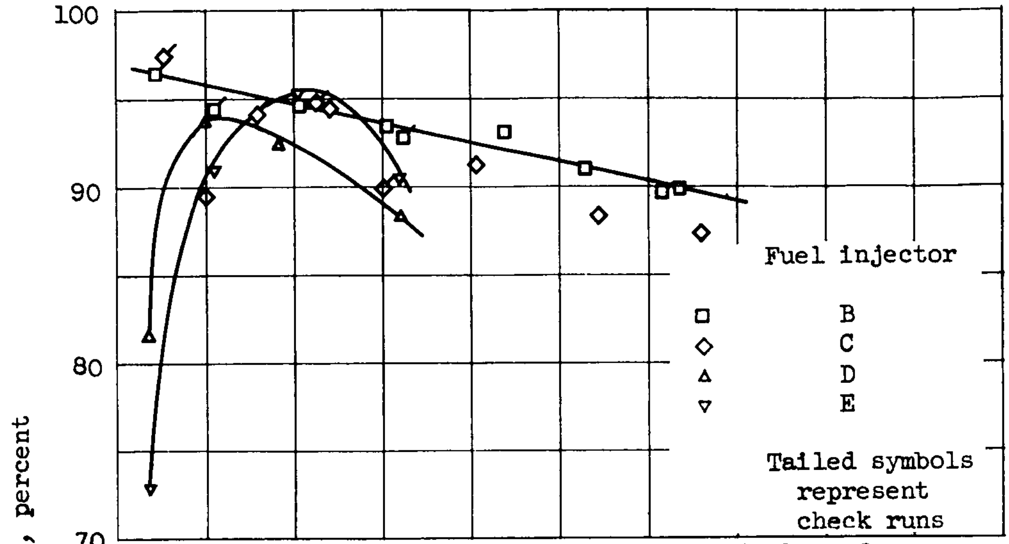
(c) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 1.0 pound per second; inlet-air temperature, 200° F; reference velocity, 132 feet per second.



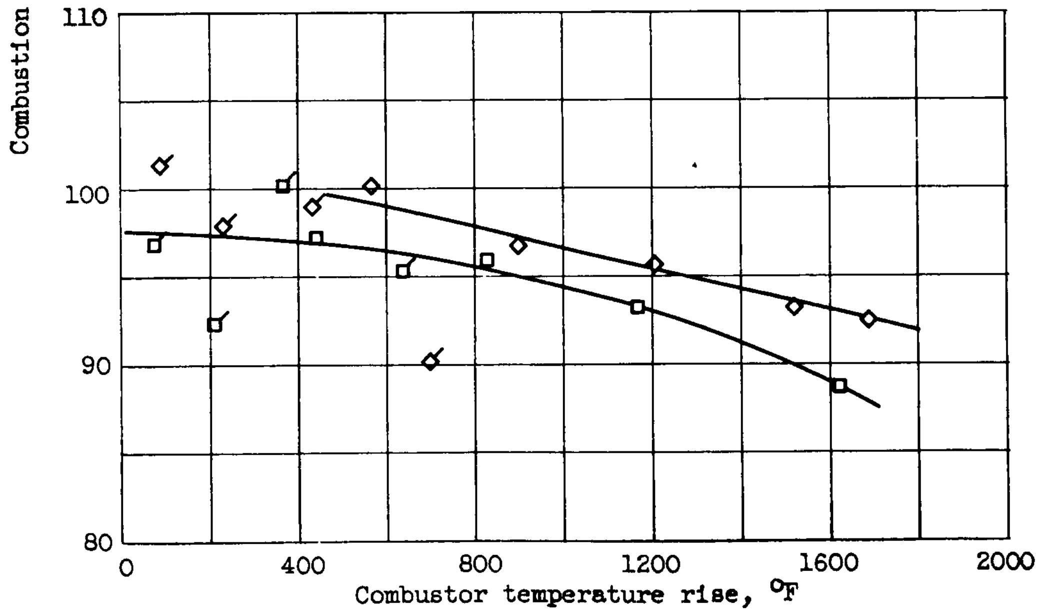
(d) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 1.0 pound per second; inlet-air temperature, 40° F; reference velocity, 100 feet per second.

Figure 8. - Continued. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

3614



(e) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 1.3 pounds per second; inlet-air temperature, 200° F; reference velocity, 173 feet per second.



(f) Combustor-inlet total pressure, 14.3 inches of mercury absolute; air-flow rate, 1.3 pounds per second; inlet-air temperature, 40° F; reference velocity, 131 feet per second.

Figure 8. - Continued. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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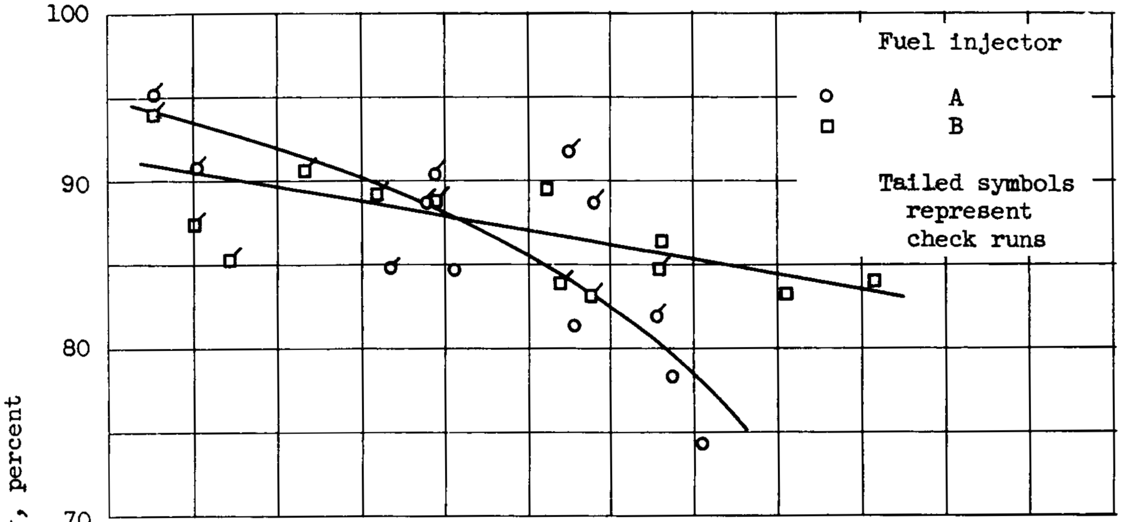
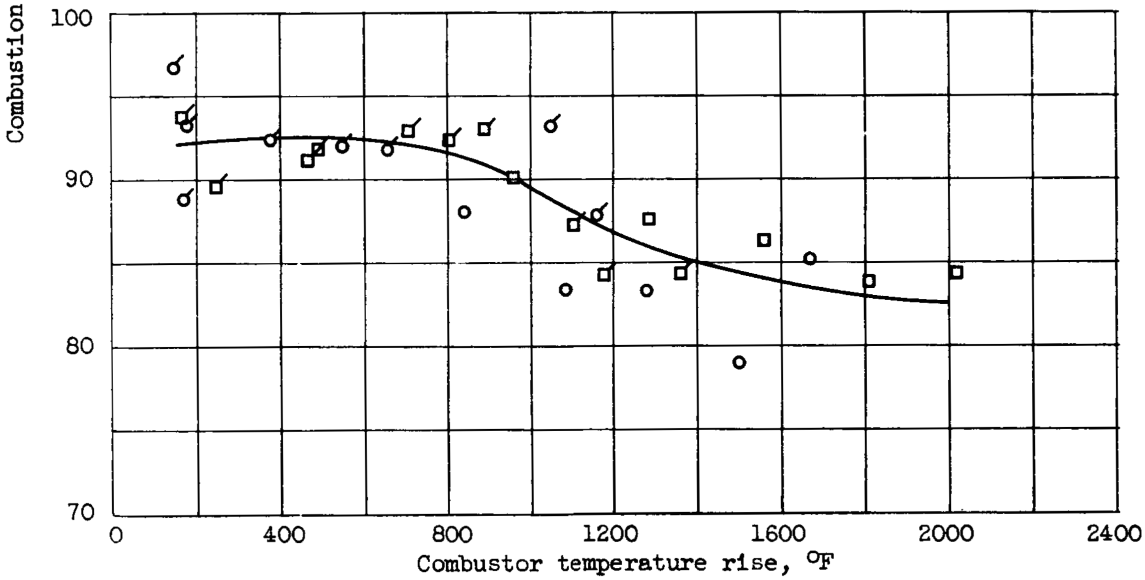


(g) Combustor-inlet total pressure, 8.0 inches of mercury absolute; airflow rate, 0.56 pound per second; inlet-air temperature, 200° F; reference velocity, 133 feet per second.



(h) Combustor-inlet total pressure, 8.0 inches of mercury absolute; airflow rate, 0.56 pound per second; inlet-air temperature, 40° F; reference velocity, 100 feet per second.

Figure 8. - Continued. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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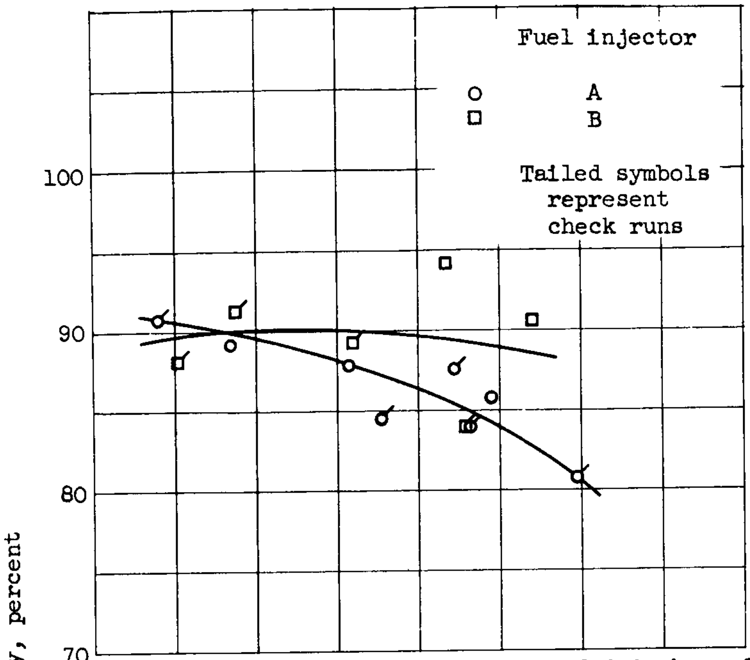
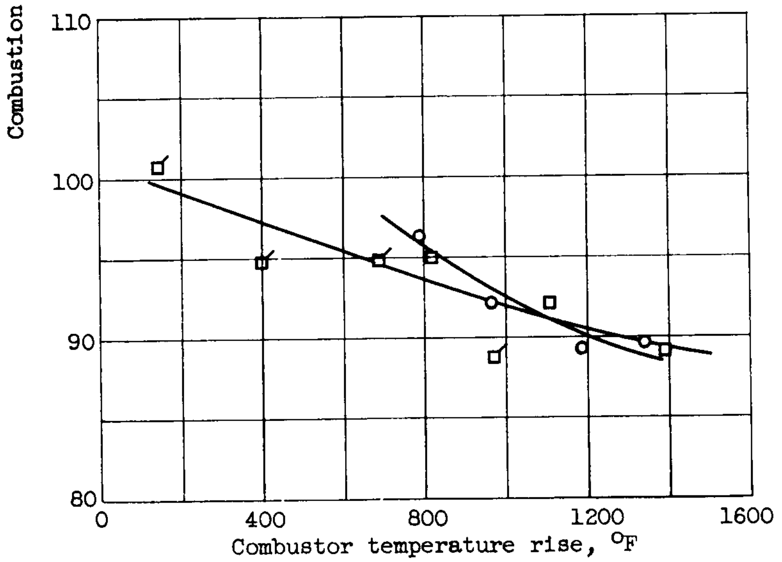


(i) Combustor-inlet total pressure, 8.0 inches of mercury absolute; air-flow rate, 0.73 pound per second; inlet-air temperature, 200° F; reference velocity, 174 feet per second.



(j) Combustor-inlet total pressure, 8.0 inches of mercury absolute; air-flow rate, 0.73 pound per second; inlet-air temperature, 40° F; reference velocity, 132 feet per second.

Figure 8. - Continued. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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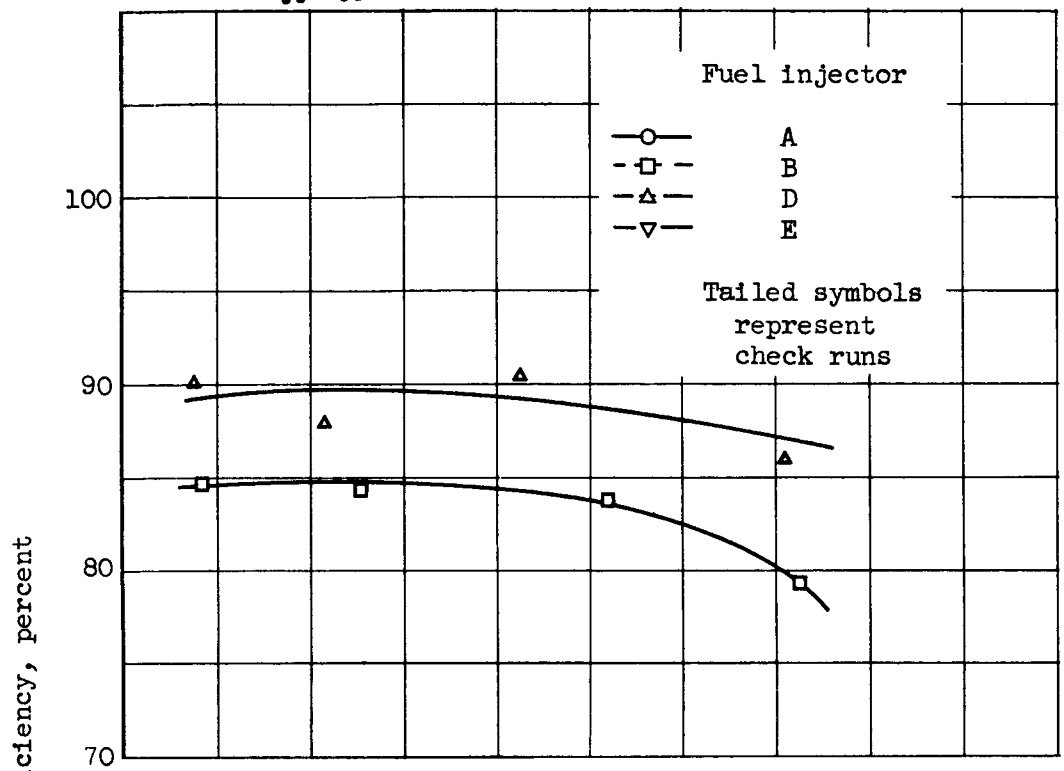
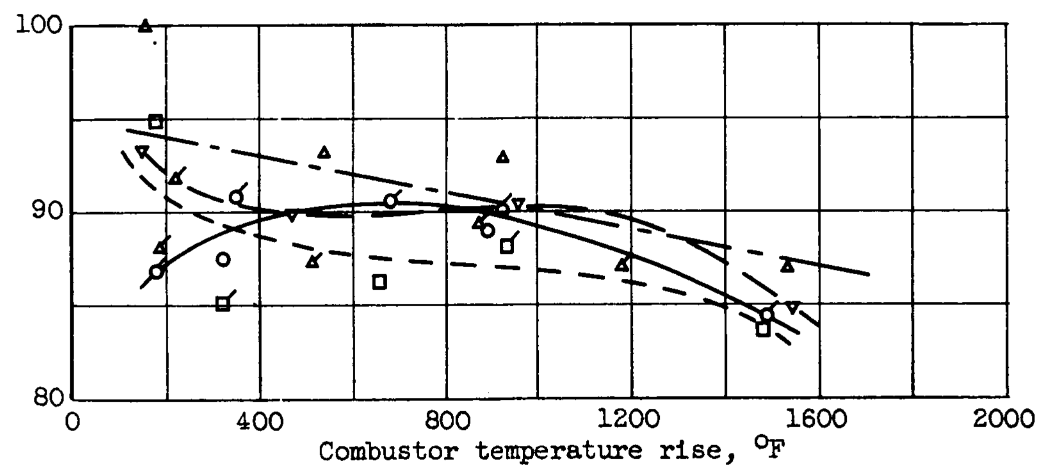


(k) Combustor-inlet total pressure, 6.2 inches of mercury absolute; air-flow rate, 0.50 pound per second; inlet-air temperature, 200° F; reference velocity, 153 feet per second.



(l) Combustor-inlet total pressure, 6.2 inches of mercury absolute; air-flow rate, 0.50 pound per second; inlet-air temperature, 40° F; reference velocity, 115 feet per second.

Figure 8. - Continued. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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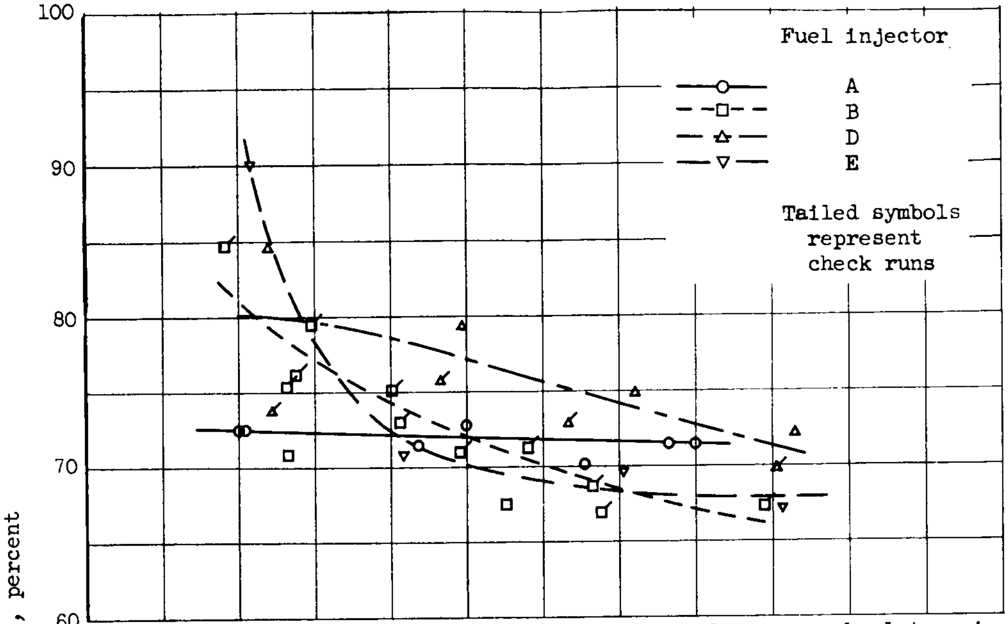
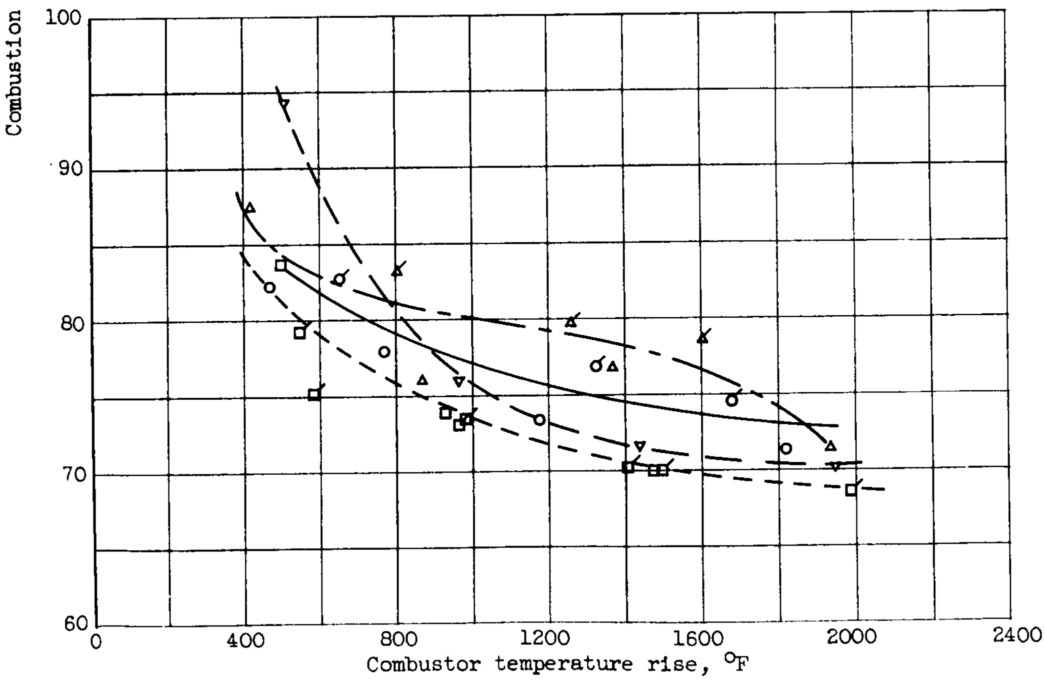


(m) Combustor-inlet total pressure, 3.3 inches of mercury absolute; air-flow rate, 0.15 pound per second; inlet-air temperature, 200° F; reference velocity, 83 feet per second.



(n) Combustor-inlet total pressure, 3.3 inches of mercury absolute; air-flow rate, 0.15 pound per second; inlet-air temperature, 40° F; reference velocity, 65 feet per second.

Figure 8. - Concluded. Variation of combustion efficiency with temperature rise for hydrogen fuel in single tubular combustor.

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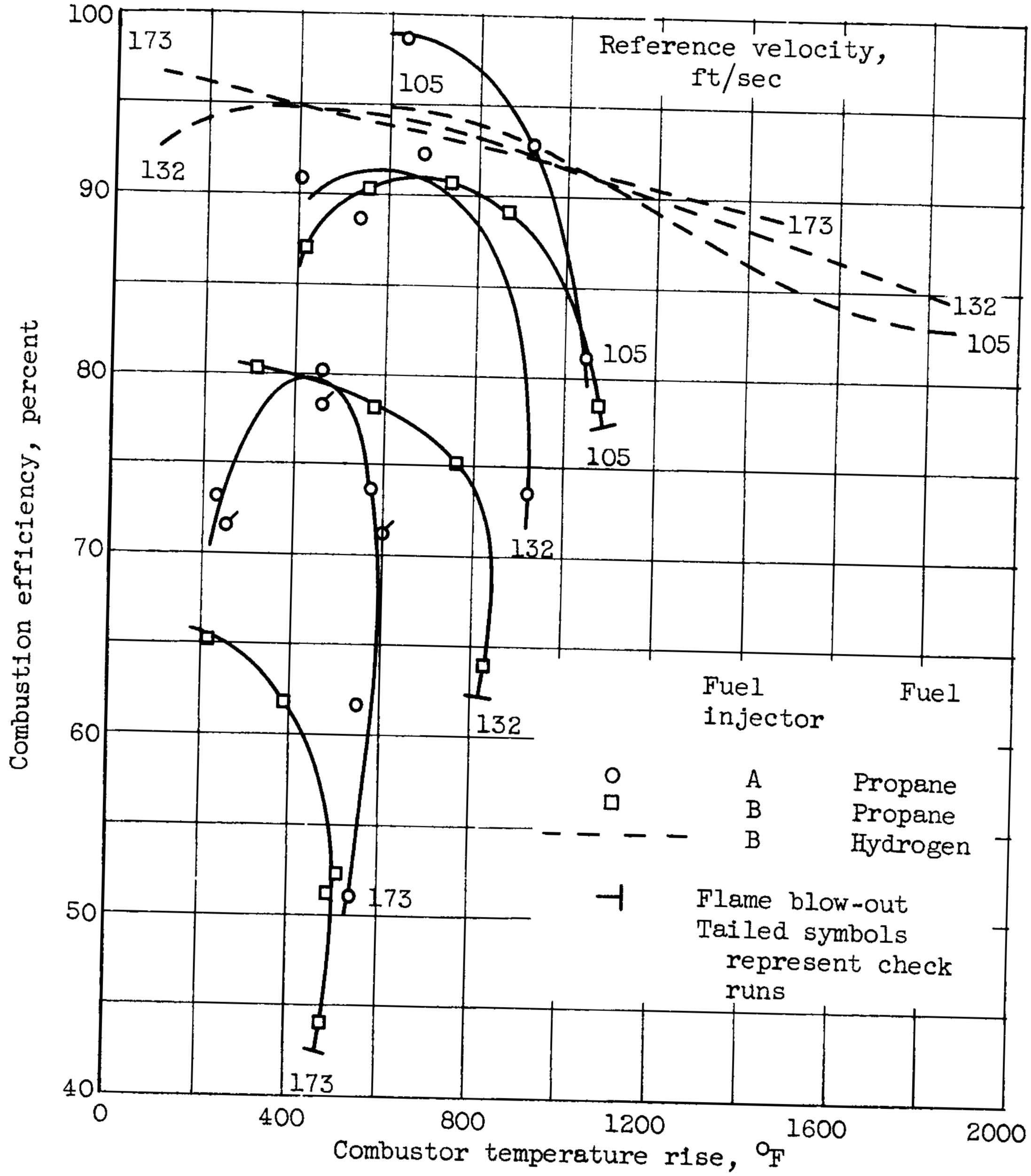
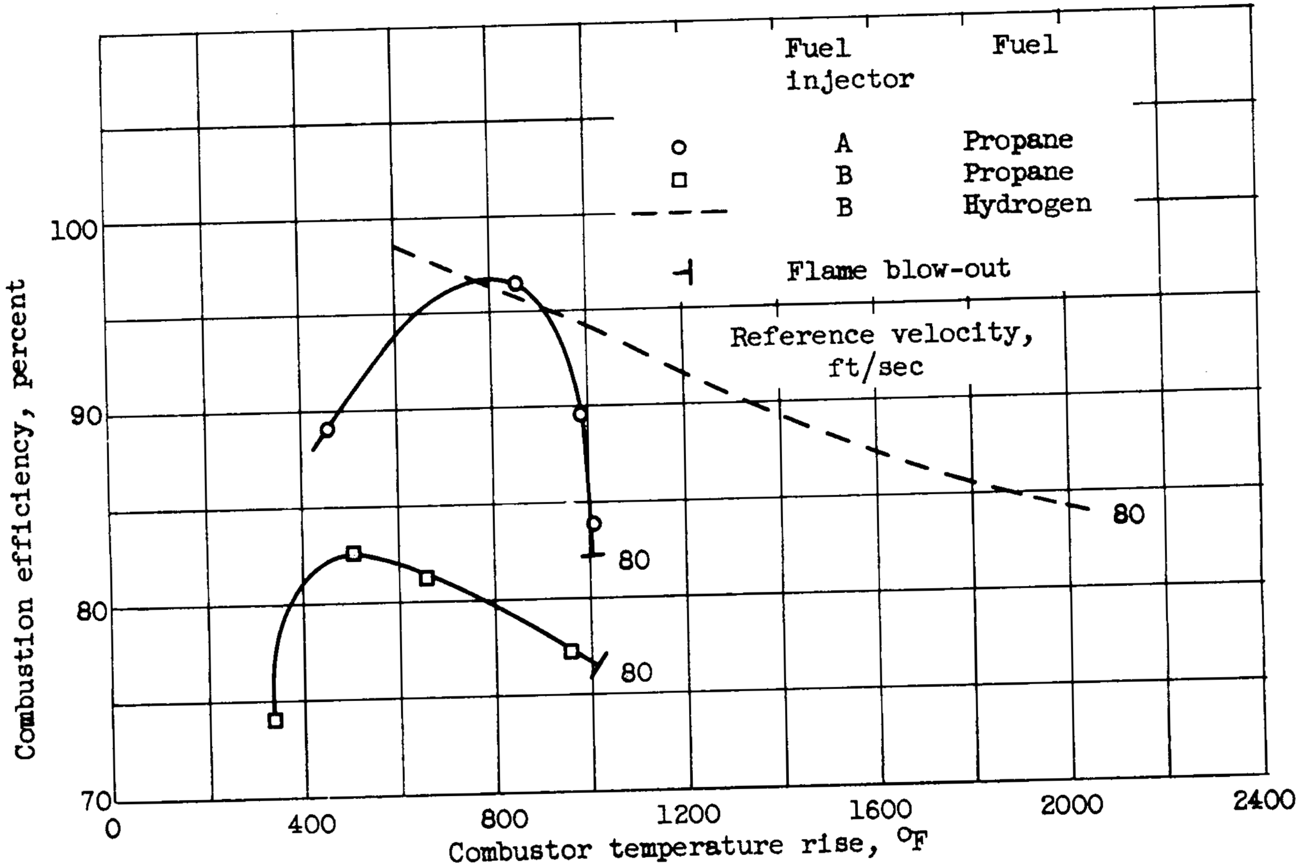


(a) Combustor-inlet total pressure, 14.3 inches of mercury absolute; inlet-air temperature, 200° F.

Figure 9. - Variation of combustion efficiency with temperature rise for propane fuel in single tubular combustor and comparison with that for hydrogen fuel.

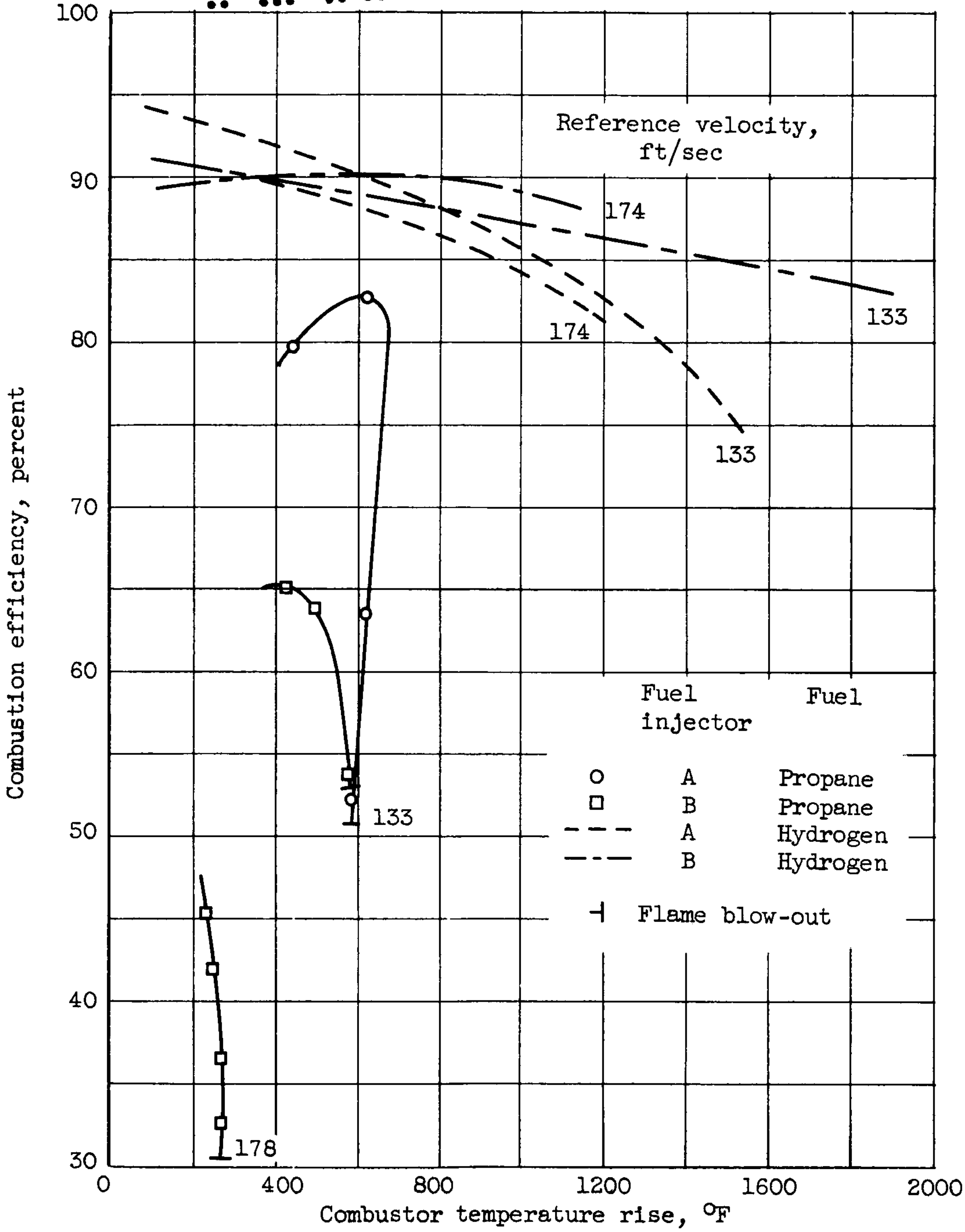
[redacted]



(b) Combustor-inlet total pressure, 14.3 inches of mercury absolute; inlet-air temperature, 40° F.

Figure 9. - Continued. Variation of combustion efficiency with temperature rise for propane fuel in single tubular combustor and comparison with that for hydrogen fuel.

[redacted]



(c) Combustor-inlet total pressure, 8.0 inches of mercury absolute; inlet-air temperature, 200° F.

Figure 9. - Concluded. Variation of combustion efficiency with temperature rise for propane fuel in single tubular combustor and comparison with that for hydrogen fuel.

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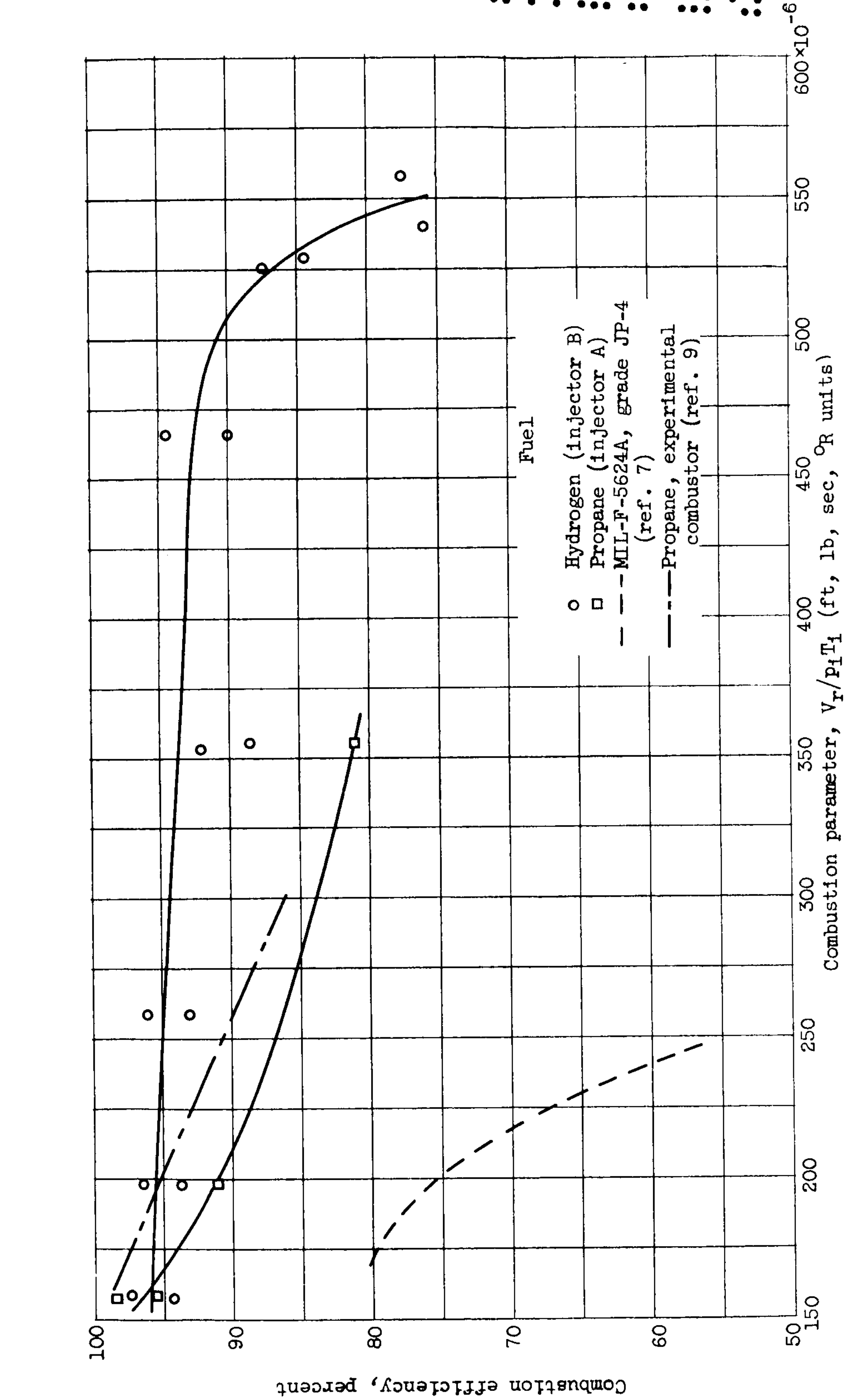
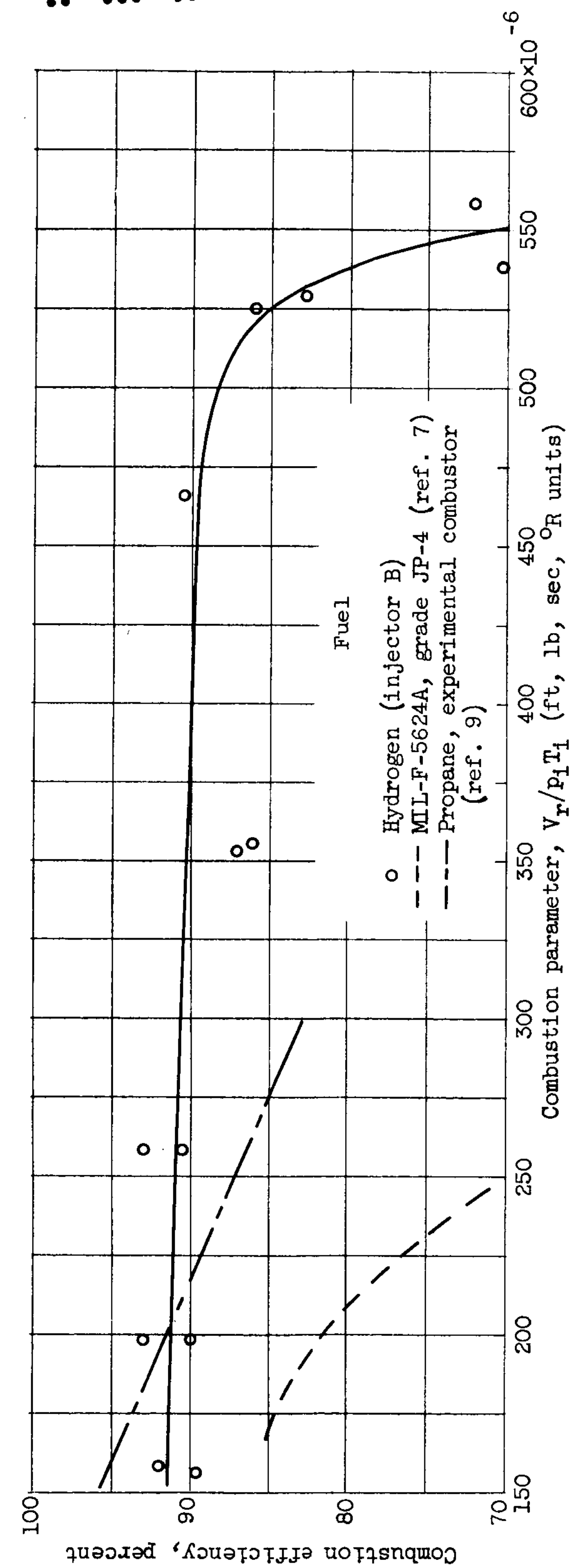


(a) Combustor temperature rise, 680° F.

Figure 10. - Correlation of combustion efficiency with combustion parameter V_r/p_1T_1.



(b) Combustor temperature rise, 1180° F.

Figure 10. - Concluded. Correlation of combustion efficiency with combustion parameter V_r/p_1T_1.

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